The Ocean's Mesoscale, its Impacts on Pelagic Ecosystems and How Satellite Viewing Changed (Created?) Interdisciplinary Oceanography

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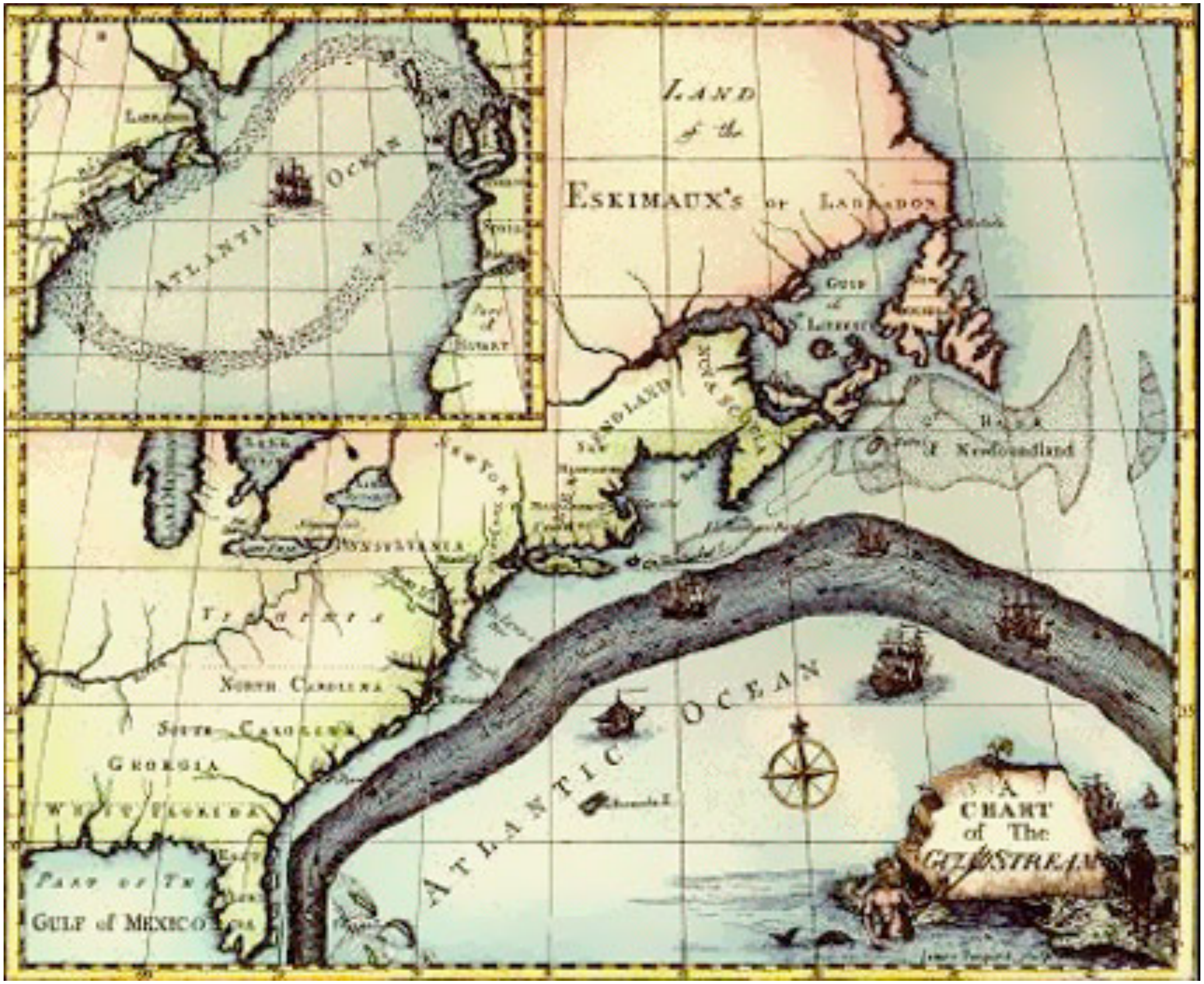
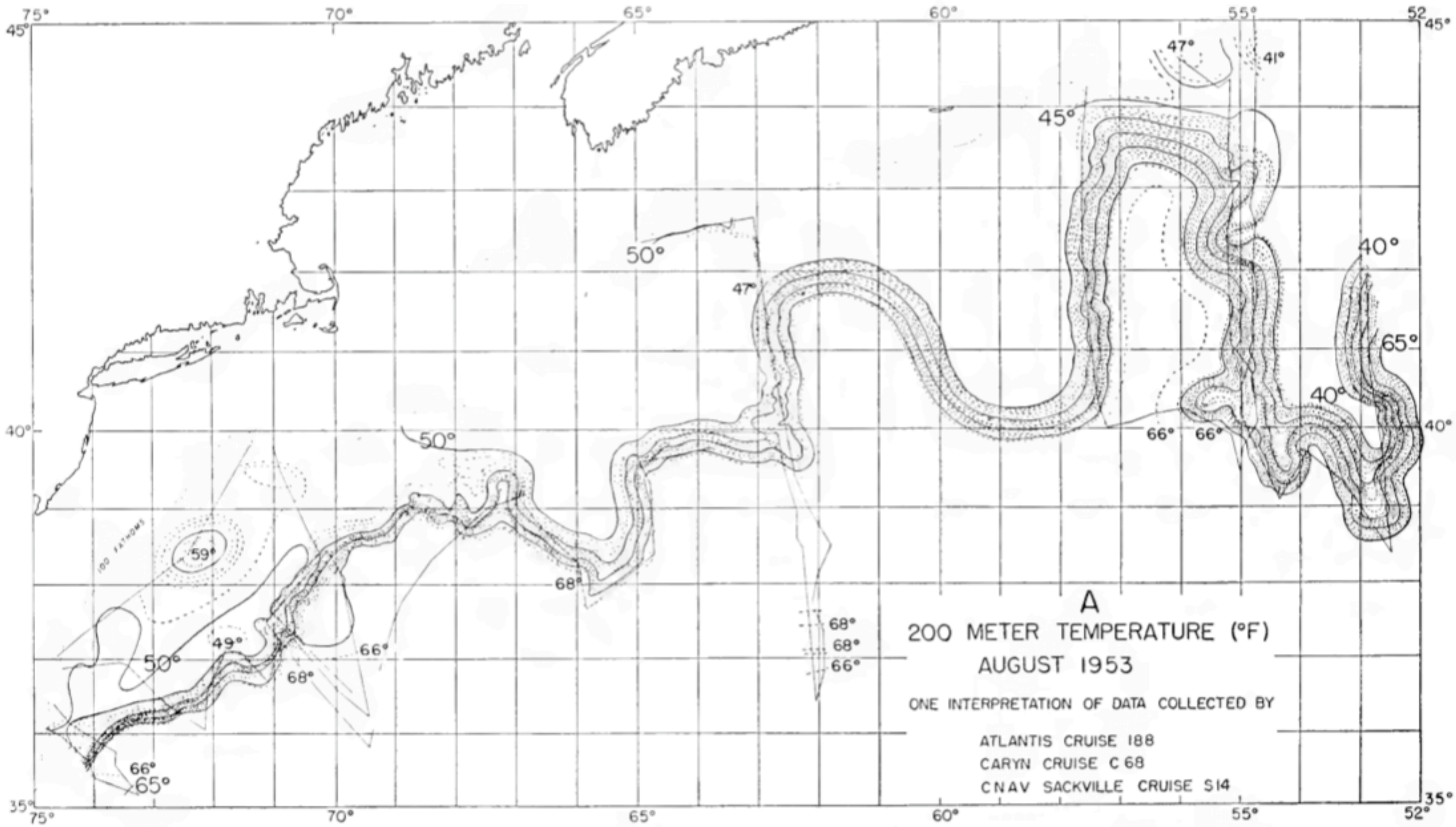
Thanx to Dennis McGillicuddy (WHOI), Dudley Chelton (OSU), Mete Uz (NSF) & many more…

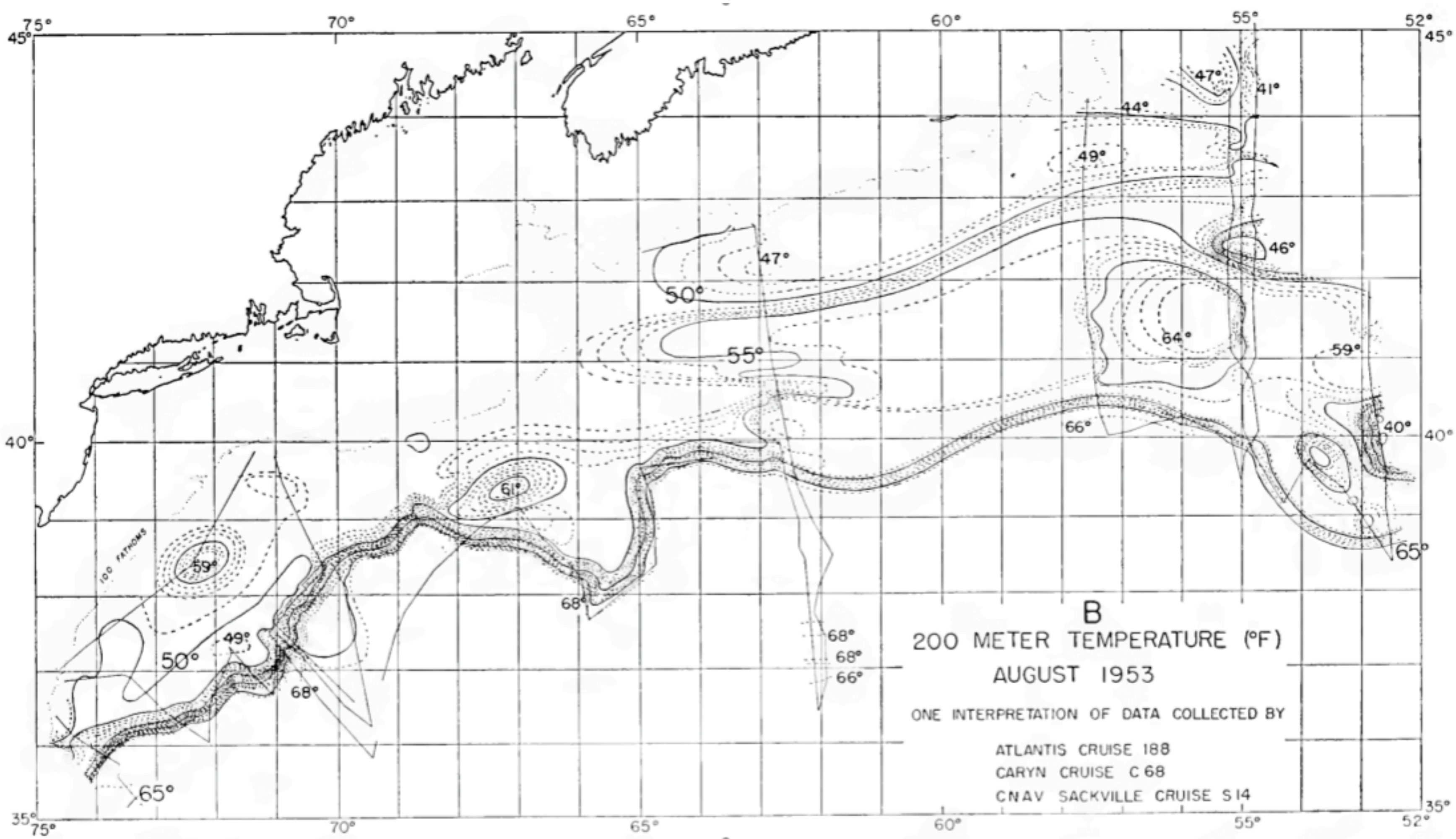
Franklin & Folgers's Gulf Stream



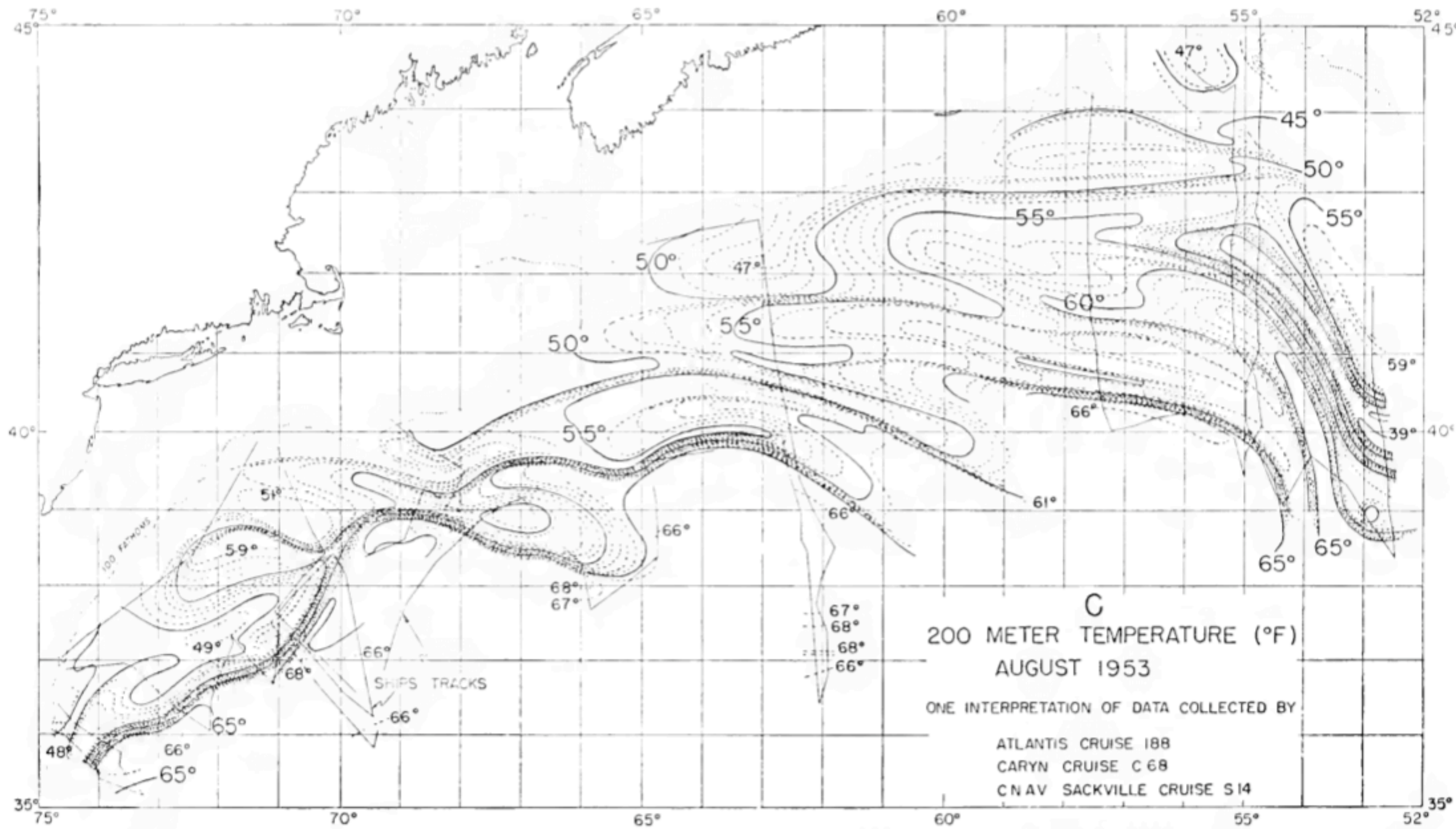
Stommel's Gulf Stream



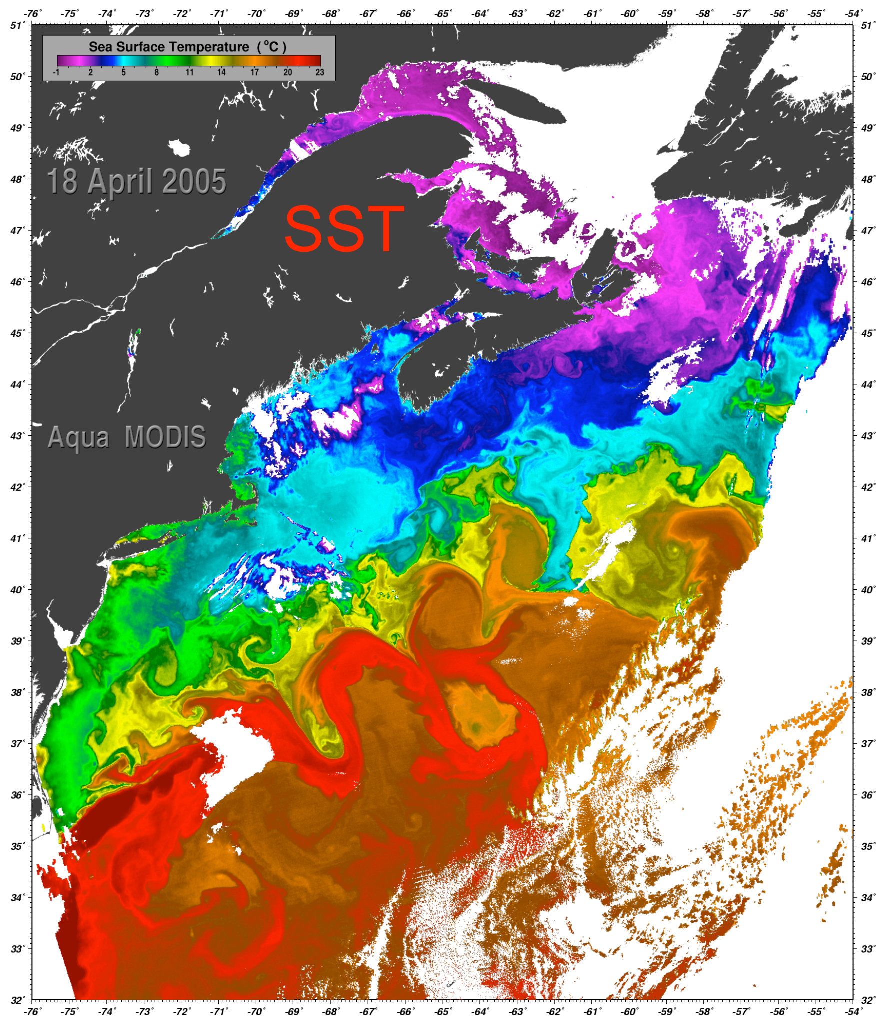
Stommel’s Gulf Stream

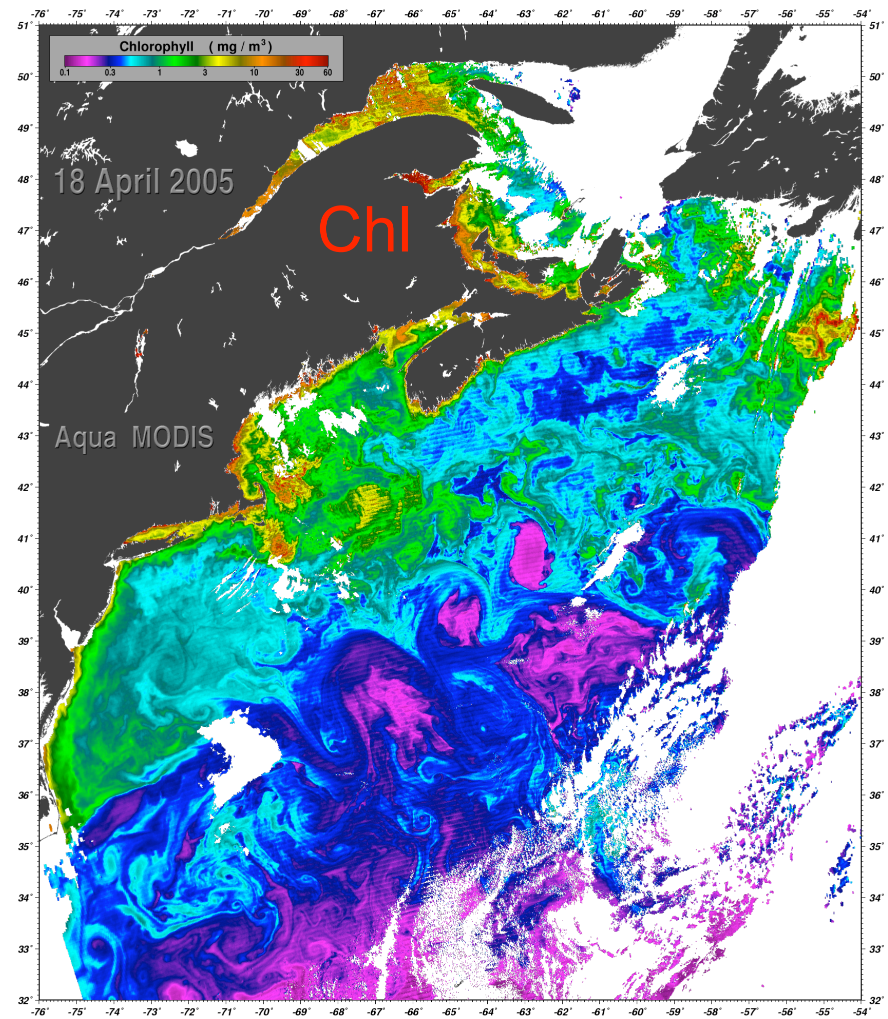


Stommel's Gulf Stream



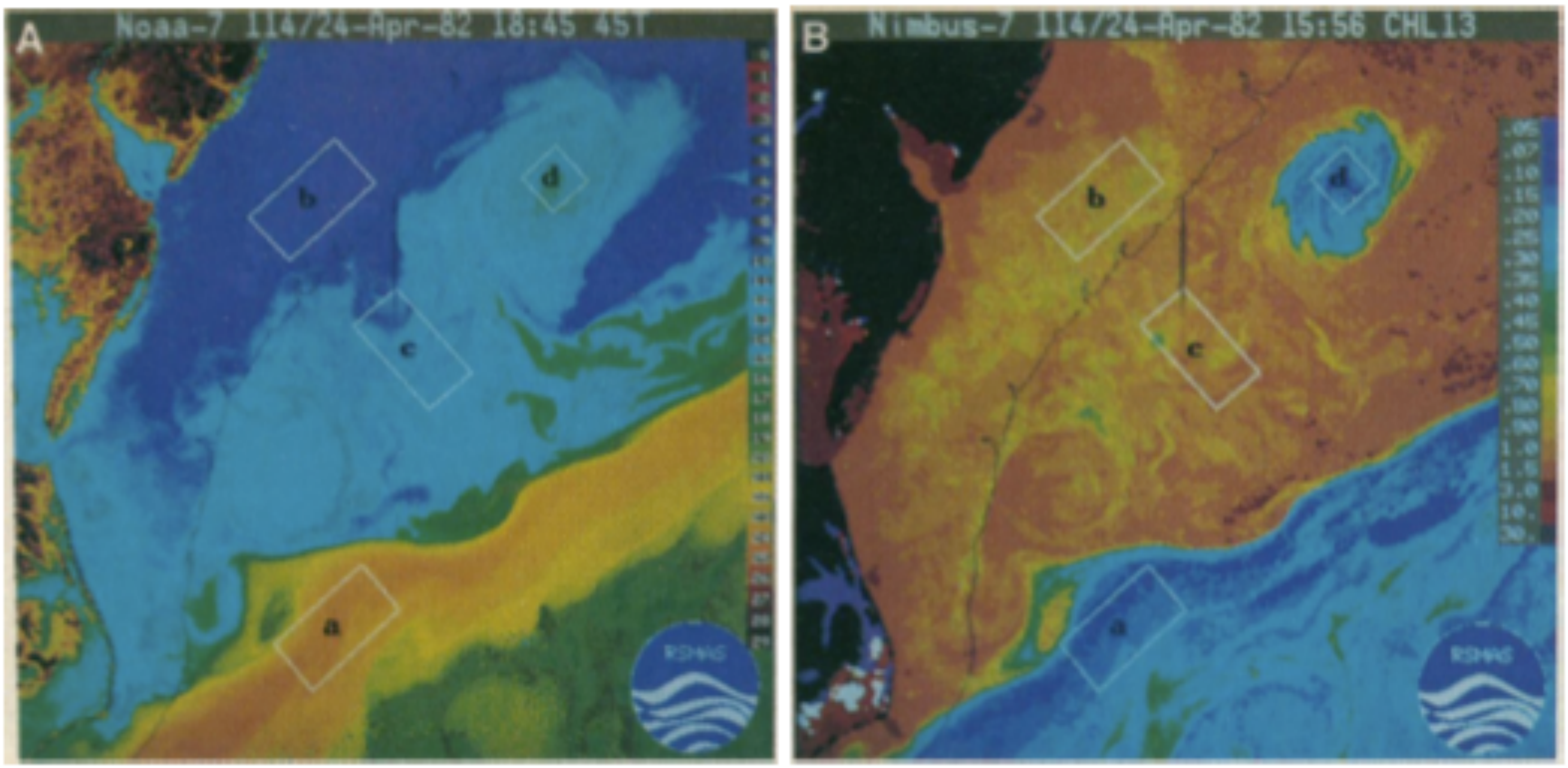
The Gulf Stream From Space





NASA GSFC Ocean Color Group

The Start of Interdisciplinary Oceanography??

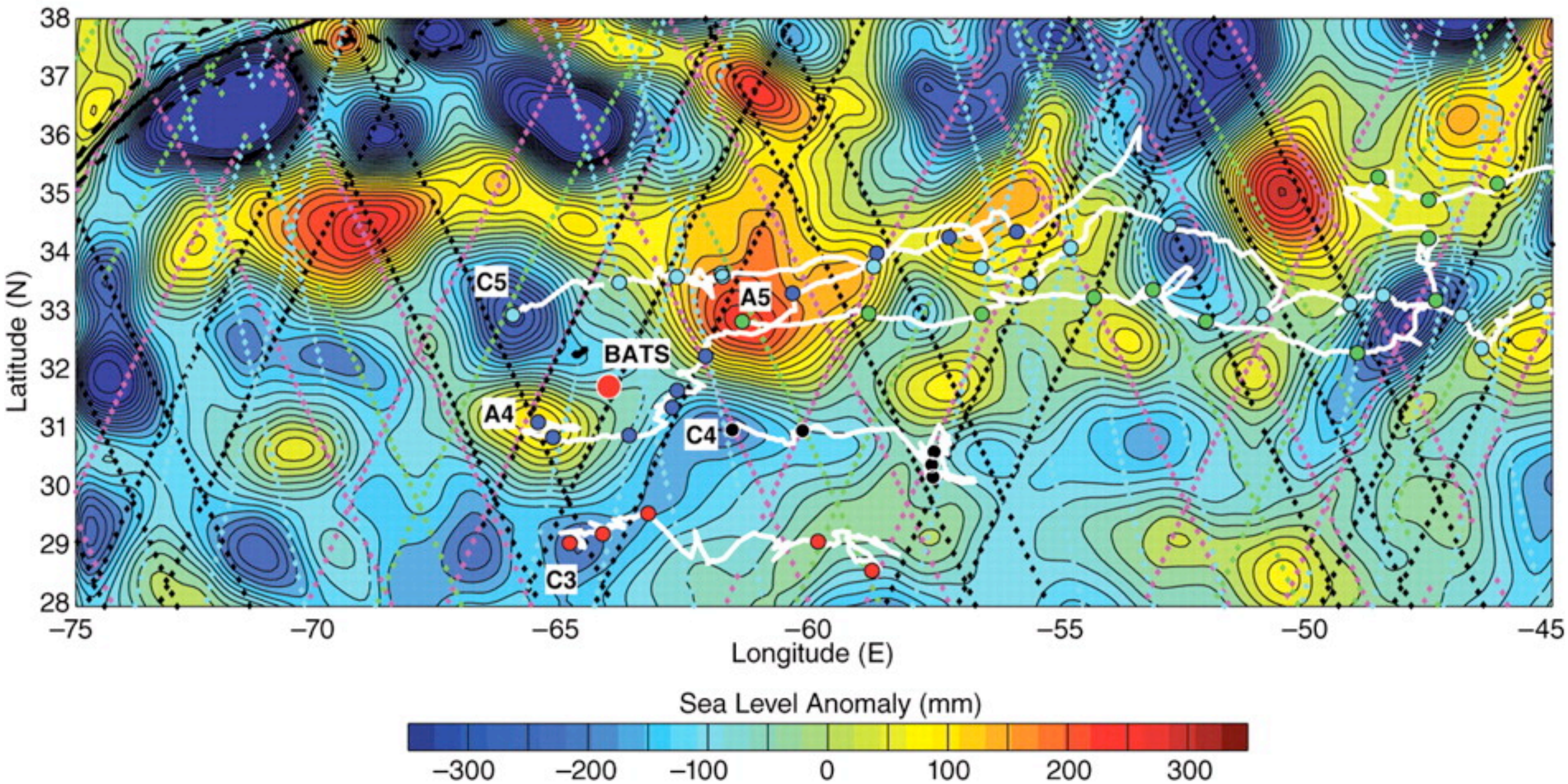


Satellite observations changed how oceanographers worked…

Warm Core Rings program

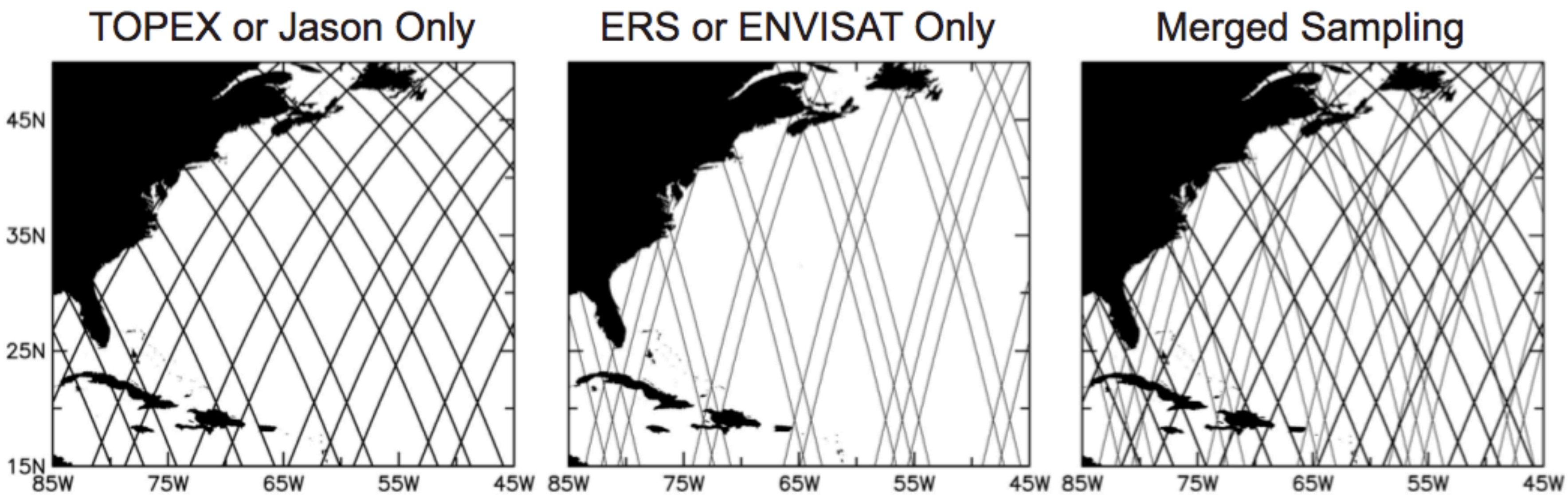
Brown et al. *Science* [1985]

Satellite Altimetry to Guide Sampling



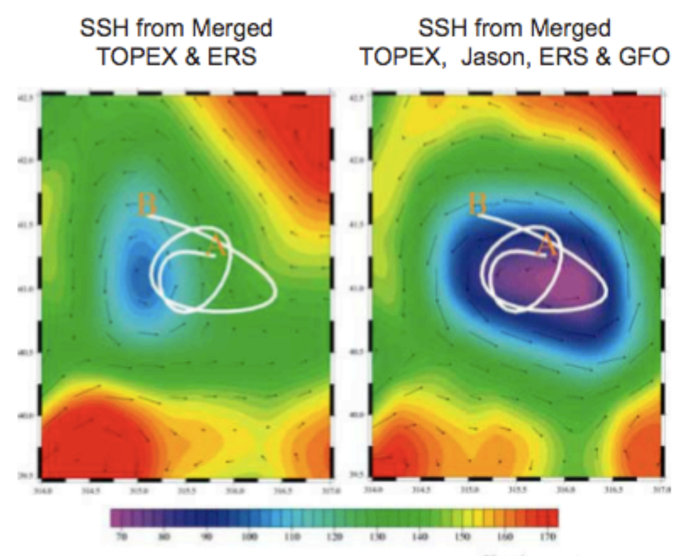
McGillicuddy et al. *Science* [2008]

Altimeter Sampling in a Representative 7-Day Period



Increased sampling enables individual eddies to be clearly assessed

Resolved the Rossby Wave / Mesoscale Eddy controversy



2 week trajectory of a surface drifter in a cyclonic eddy in the Gulf Stream

Pascual et al. *GRL* [2006]

Sea Surface Height - SSH

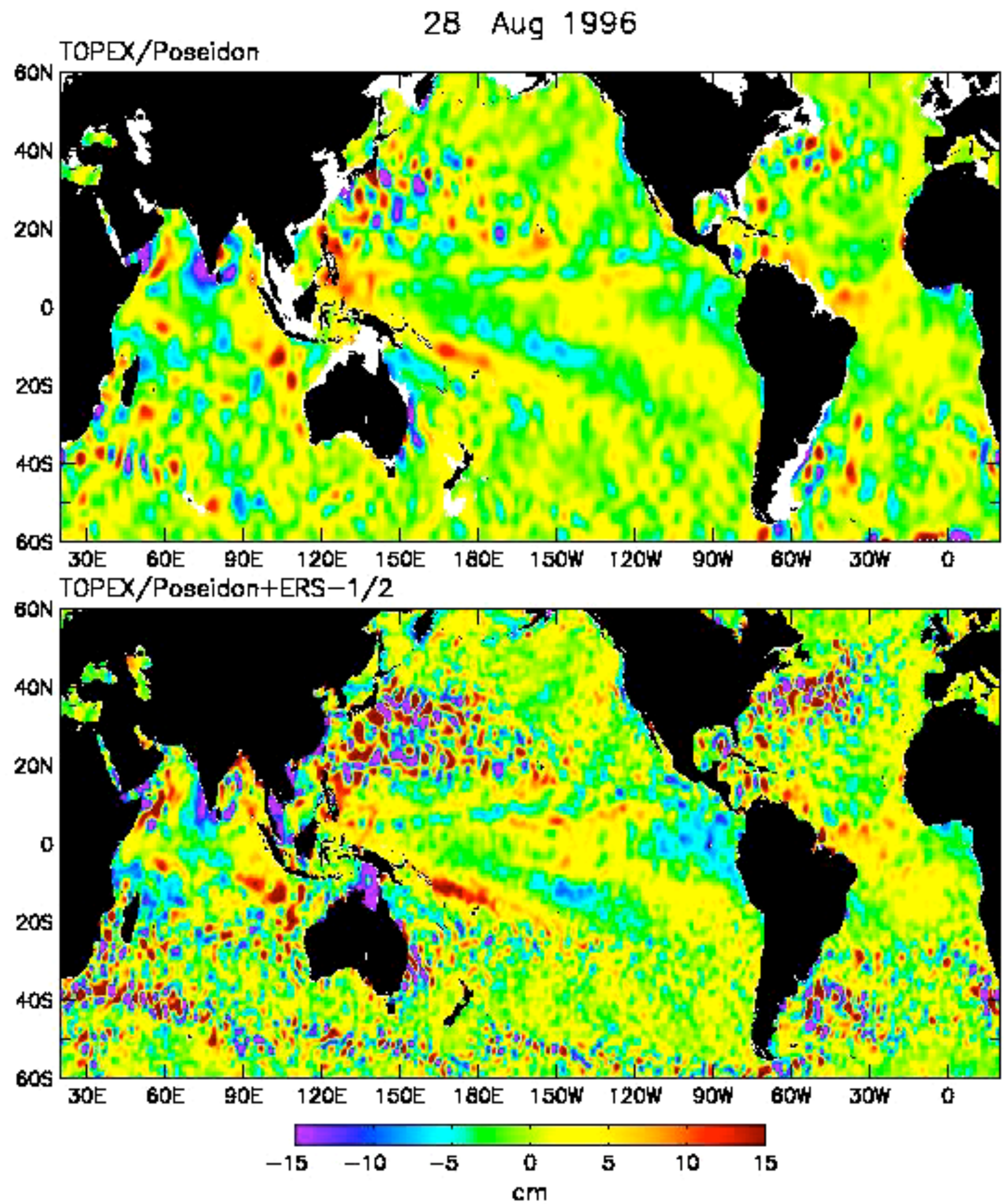
Mesoscale eddies are ubiquitous

Scales are 10's to 100's km - f(latitude)

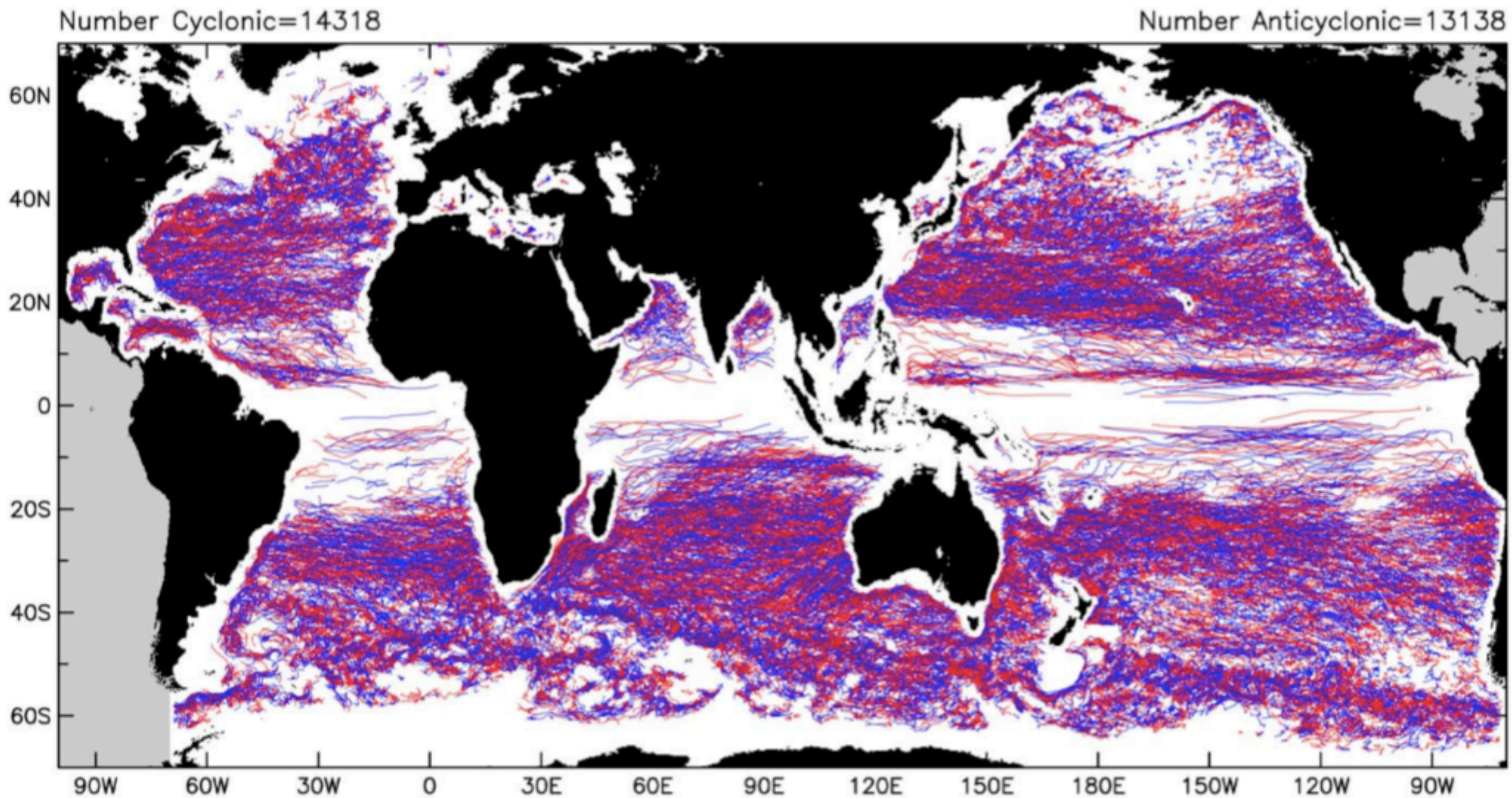
Lifetime of weeks to years

Both cyclones (CCW) & anticyclones (CW) are found

Geostrophy allows currents to be assessed



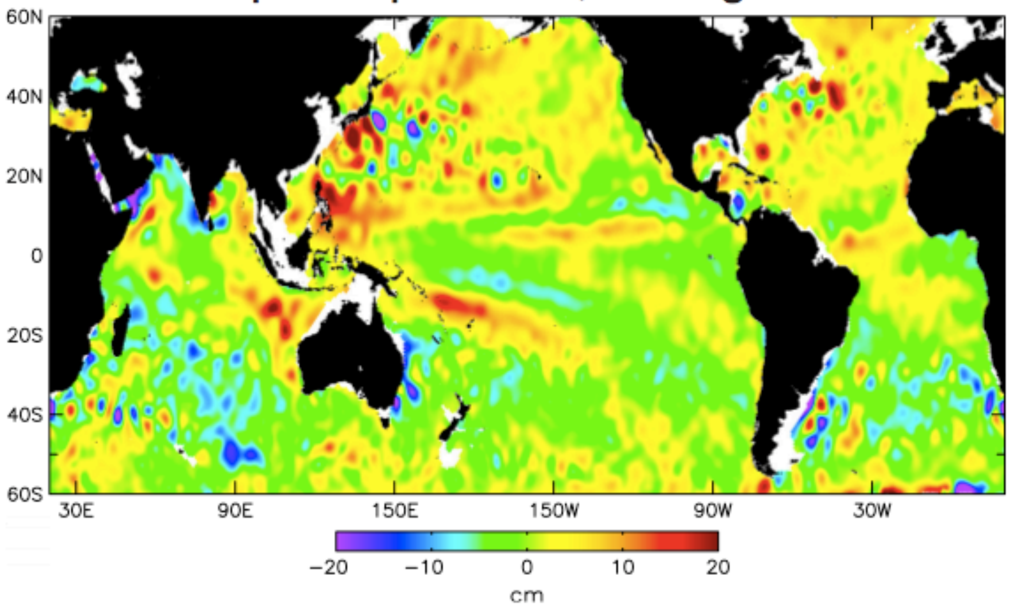
Cyclonic and Anticyclonic Eddies with Lifetimes ≥ 16 Weeks
(27,456 total)

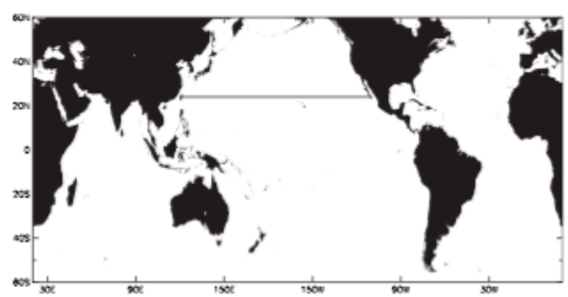


After Chelton et al. *GRL* [2007]

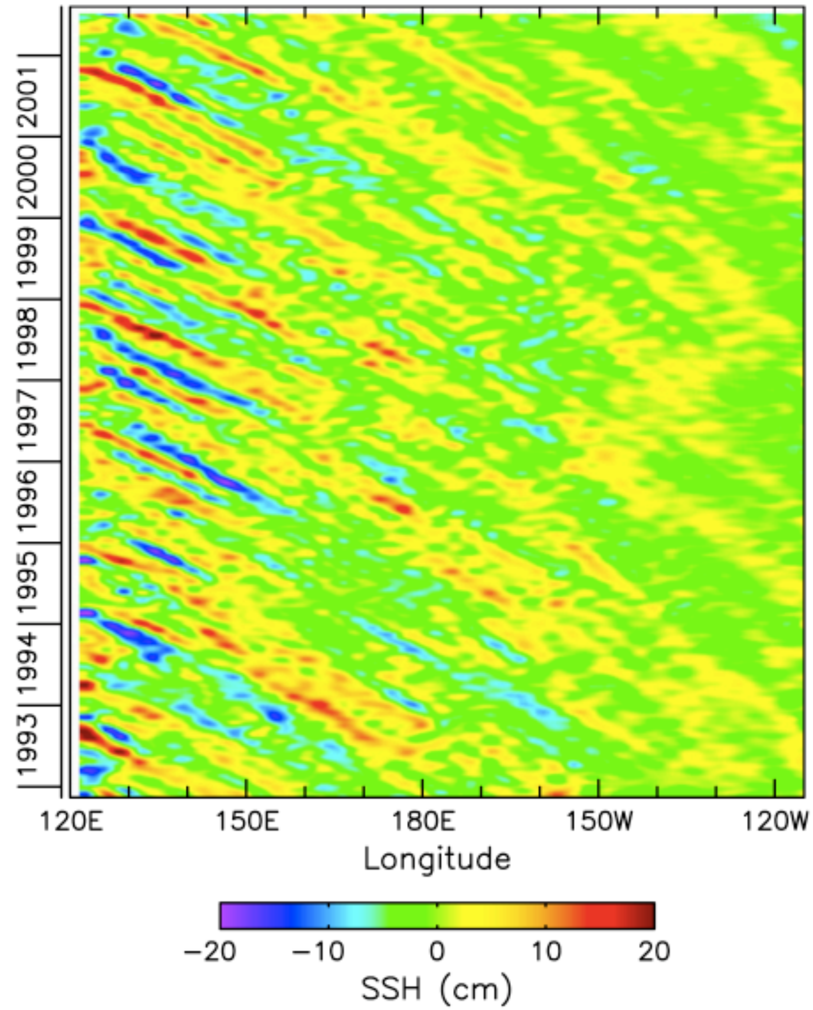
Westward Propagating Features

Example Map of SSH, 21 August 1996



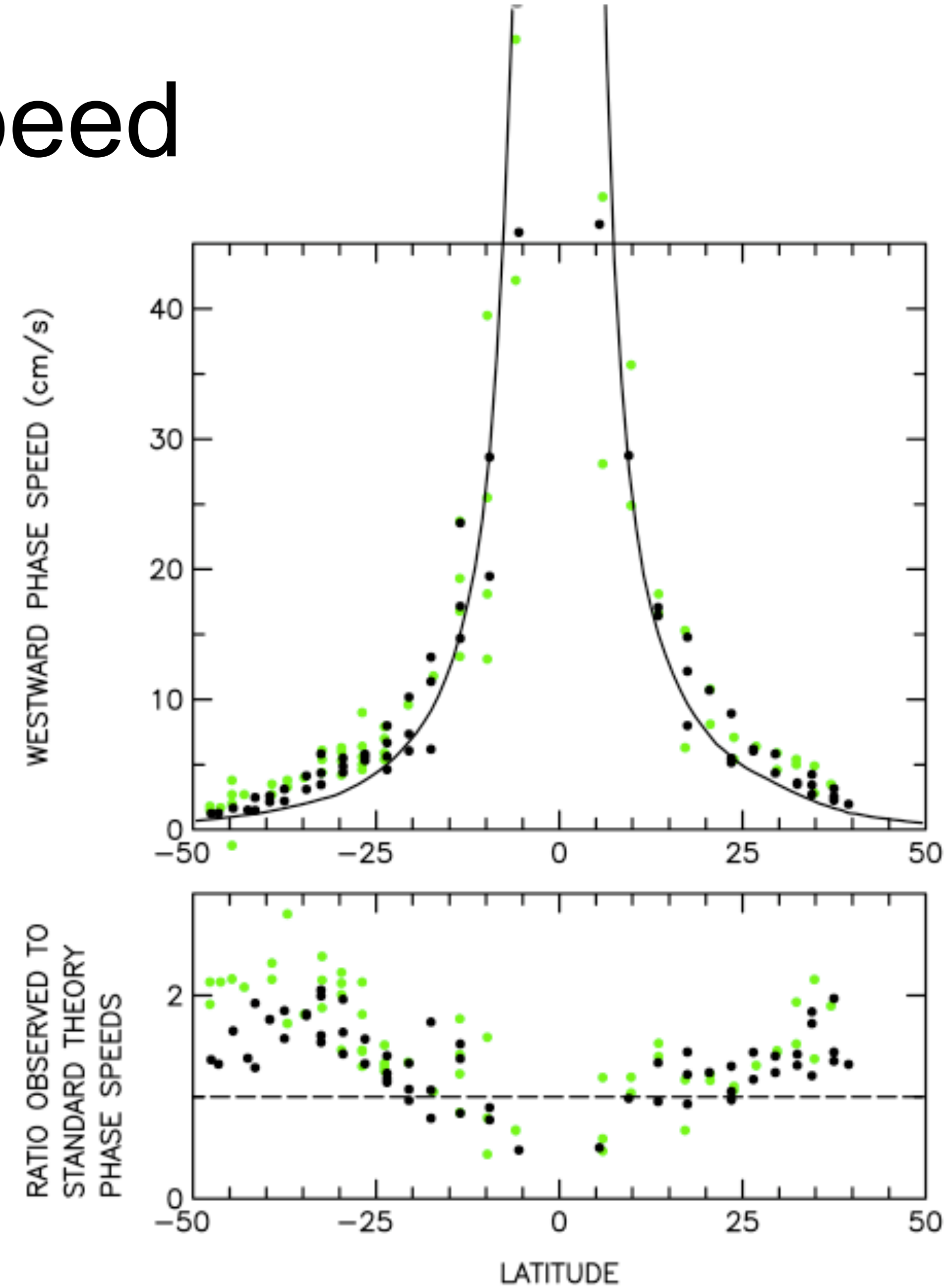


Example Time-Longitude Plot
Along 24ºN



Propagating Speed

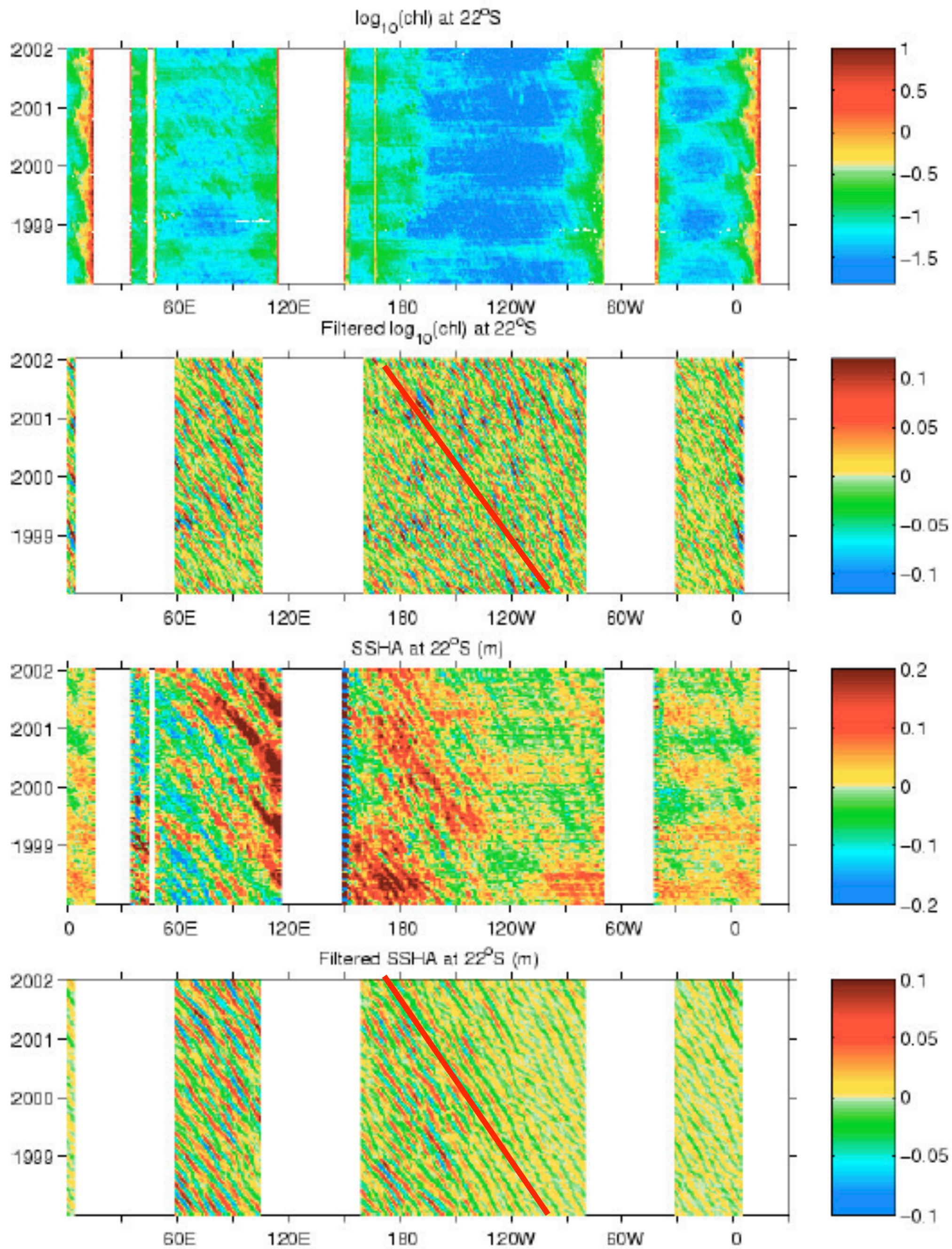
- Calculated following SSH features at a latitude
- Features propagate with speeds similar to linear Rossby waves
- Discrepancies have led to much important theoretical work
- Increased sampling makes it clear these features are eddies



Black data points from Chelton & Schlax, *Nature* [1996] - Green points show more recent observations

Biological Role of Mesoscale Eddies

- Eddies will lift & depress isopycnal surfaces & advect populations horizontally
- Seems like it should be important for the biogeochemistry & ecology of the open ocean
- Is there a biological response to the propagation of mesoscale eddies?
- If so, what does this tell us about the biological carbon pump?



Indian Pacific Atlantic

Chl along 22°S

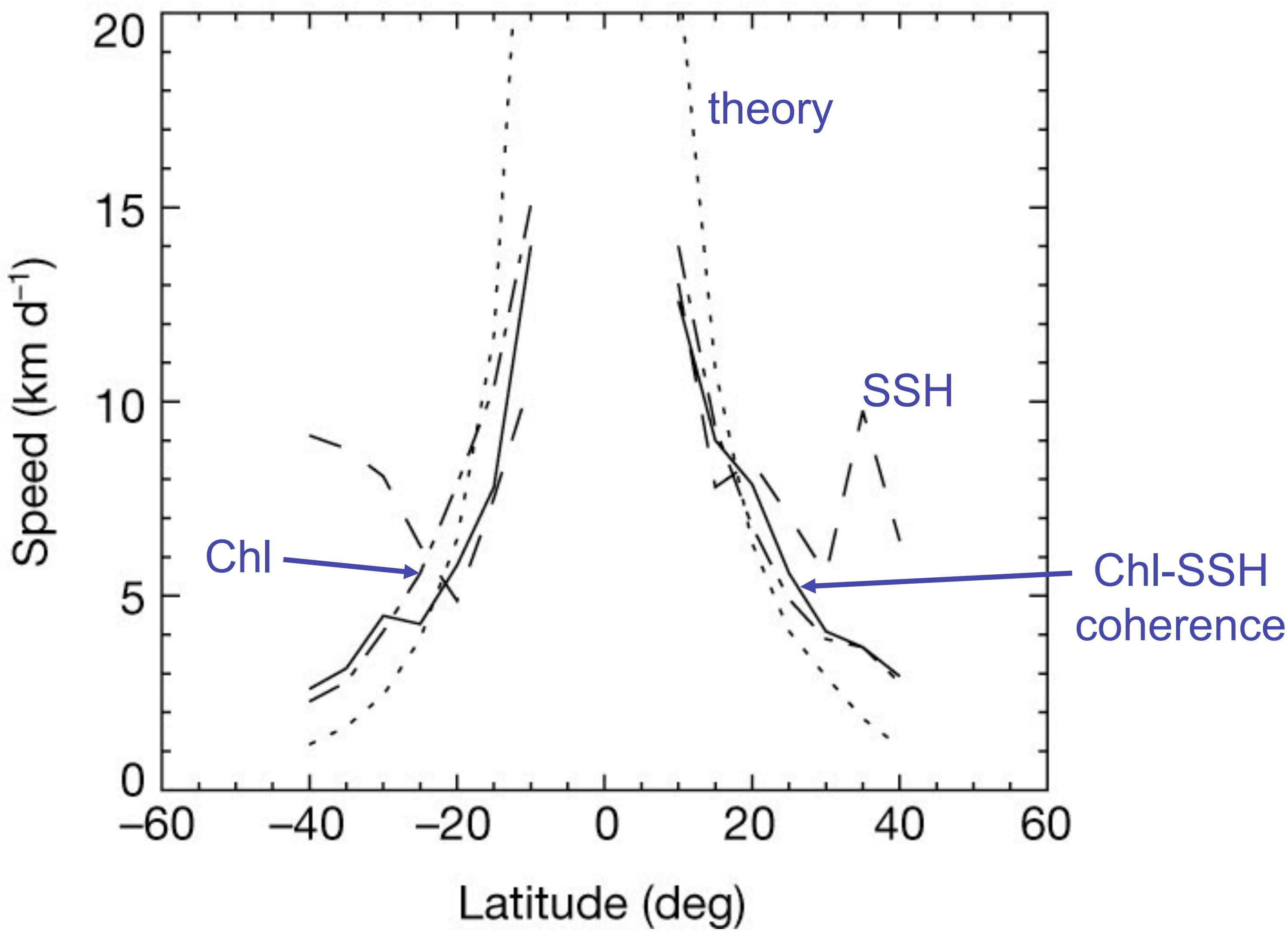
Filtered Chl anomalies

SSH along 22°S

Filtered SSH anomalies

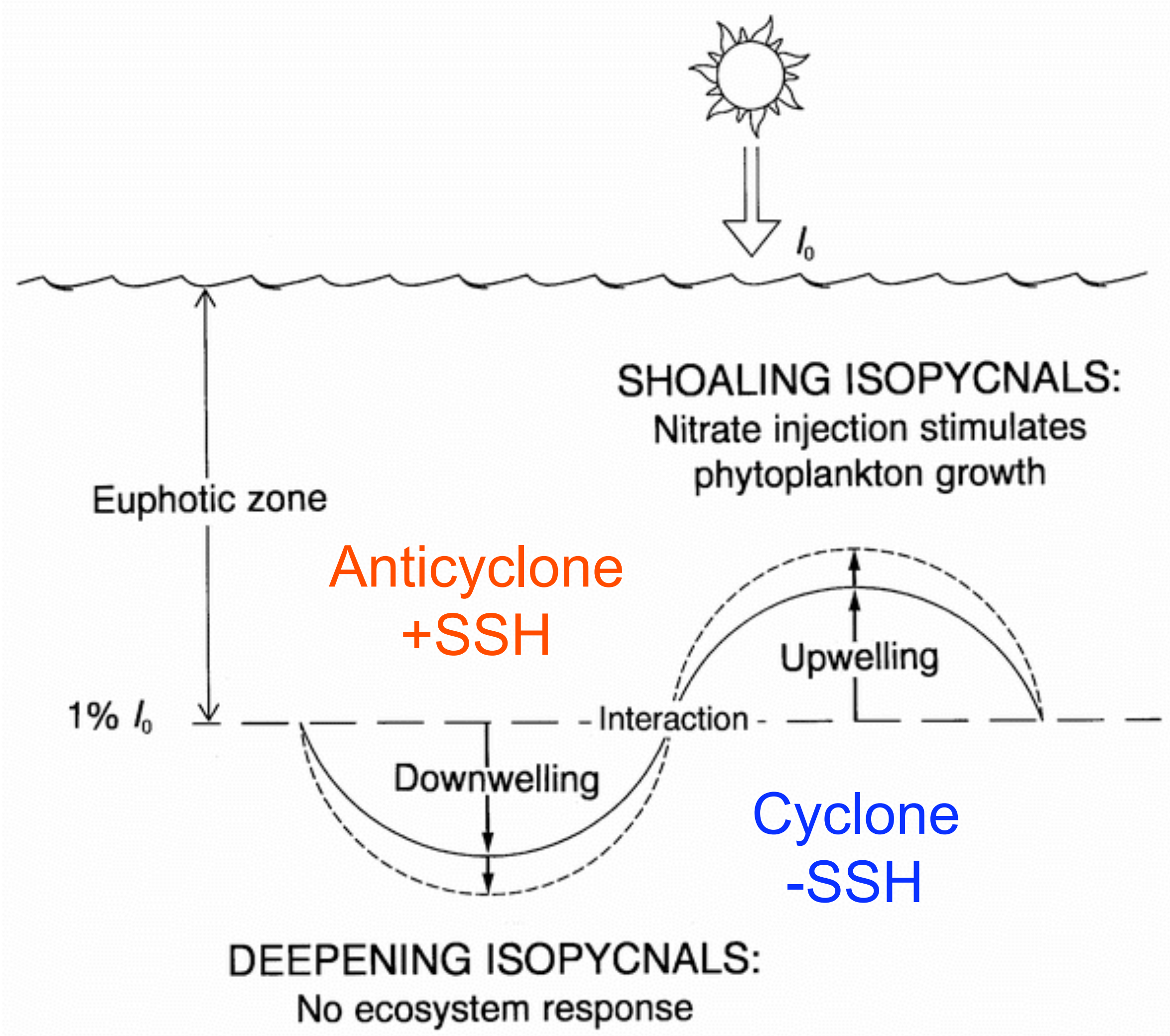
After Uz et al. *Nature* [2001]

Propagating Biological Features



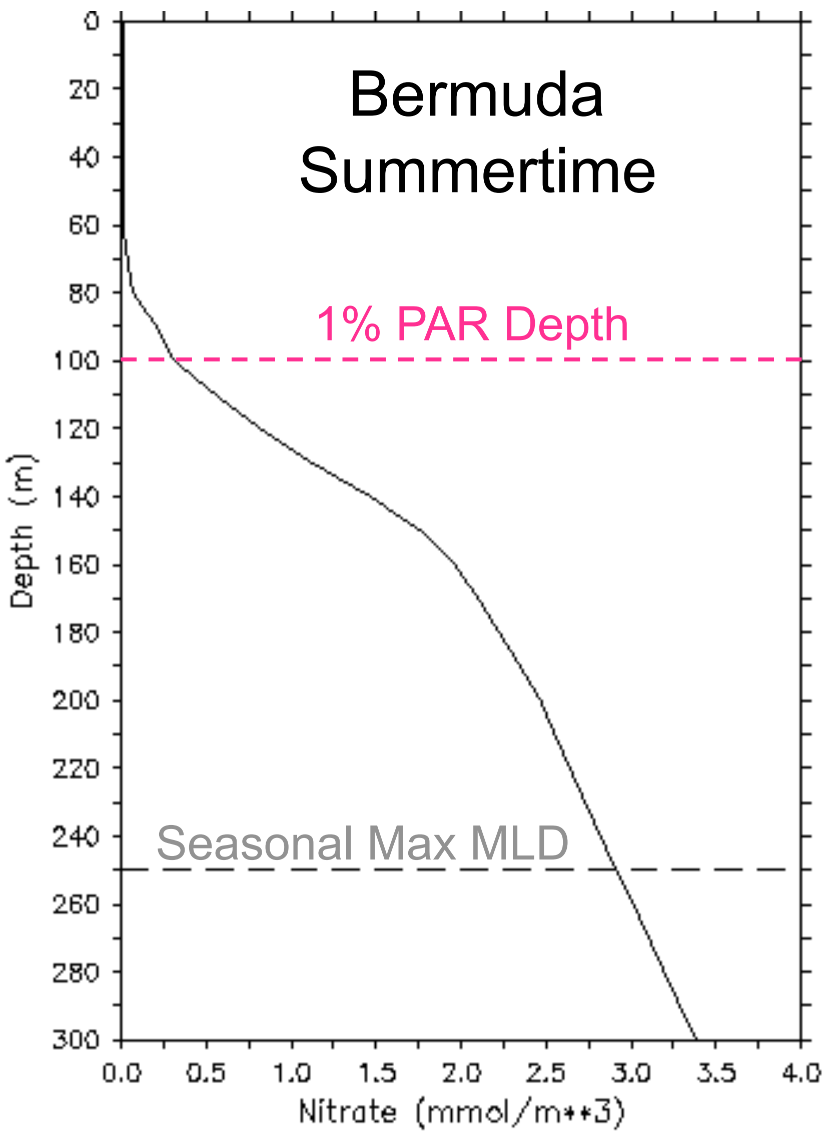
From Uz et al. *Nature* [2001]

Vertical Eddy Pumping



McGillicuddy et al. [1998] *Nature*

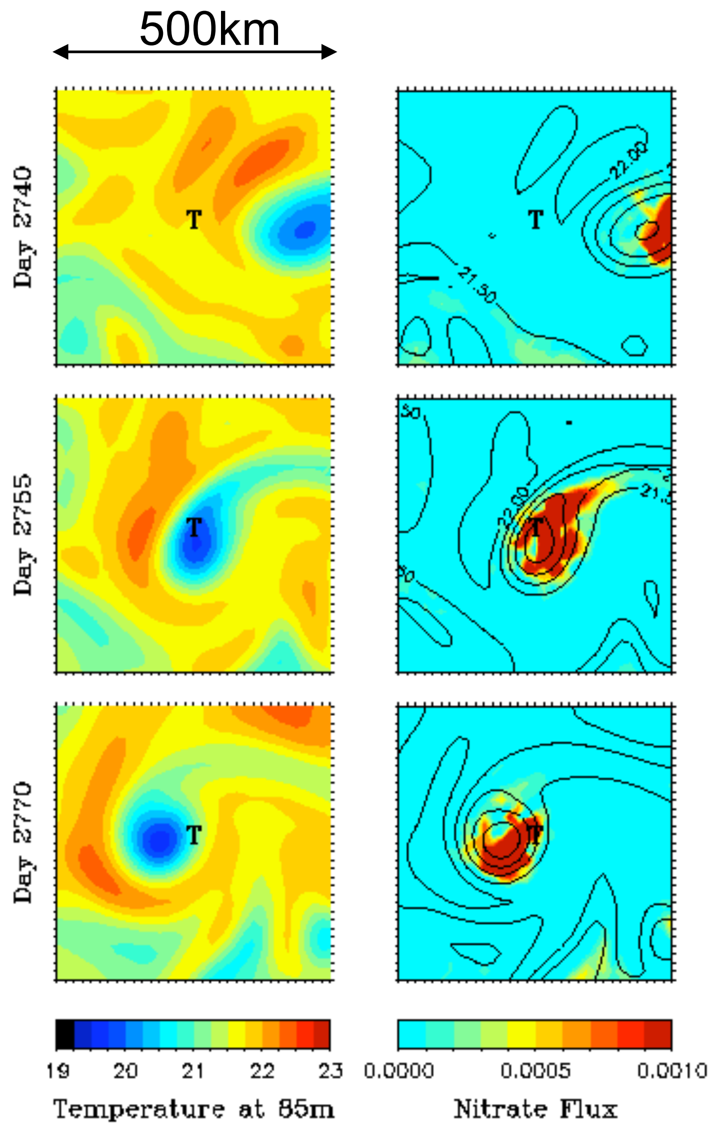
Vertical Eddy Pumping



- Mesoscale eddies will lift & depress isopycnals several 10’s to several 100 m
- This will lift & depress nutrient surfaces
- Thereby bringing nutrient replete waters into the euphotic zone

After McGillicuddy et al. *Nature* [1998]

An Eddy-driven Plankton Bloom



- Idealized eddy-resolving model of the Sargasso Sea (POLYMODE)
- Mean nitrate is f(density)
- Nitrate is removed when upwelled to the euphotic zone & remineralized if below its mean
- Nitrate flux patterns are consistent with isopycnal doming
- Supports the vertical nutrient pumping hypothesis

McGillicuddy & Robinson *DSR-I* [1997]

Impacts of Eddies and Mixing on Plankton Community Structure and Biogeochemical Cycling in the Sargasso Sea

McGillicuddy
Ledwell
Jenkins
Buesseler
Davis
Falkowski
Hansell
Siegel
Carlson
Bates
Johnson
Steinberg

WHOI · Rutgers · RSMAS · BBSR · UCSB · VIMS — EDDIES

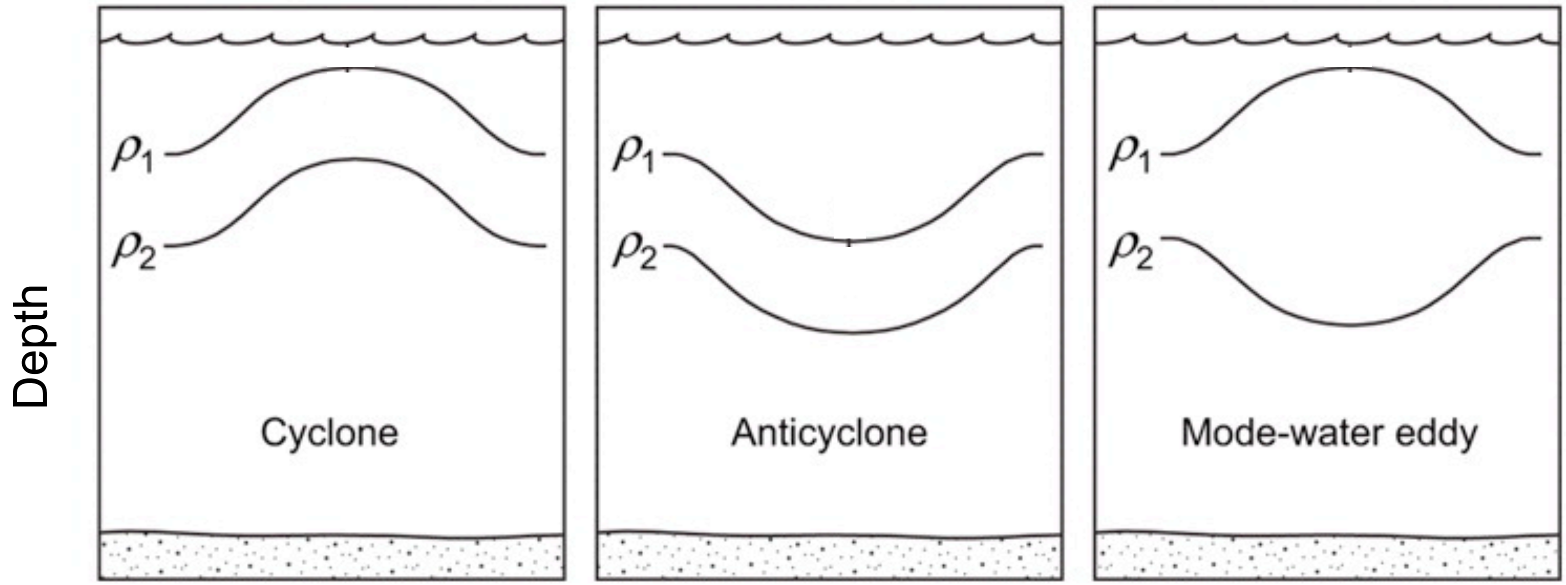

R/V *Oceanus*


R/V *Weatherbird II*

NSF NASA

http://science.whoi.edu/users/mcgillic/eddies/Eddies_Project.html

Types of Eddies in the Sargasso Sea

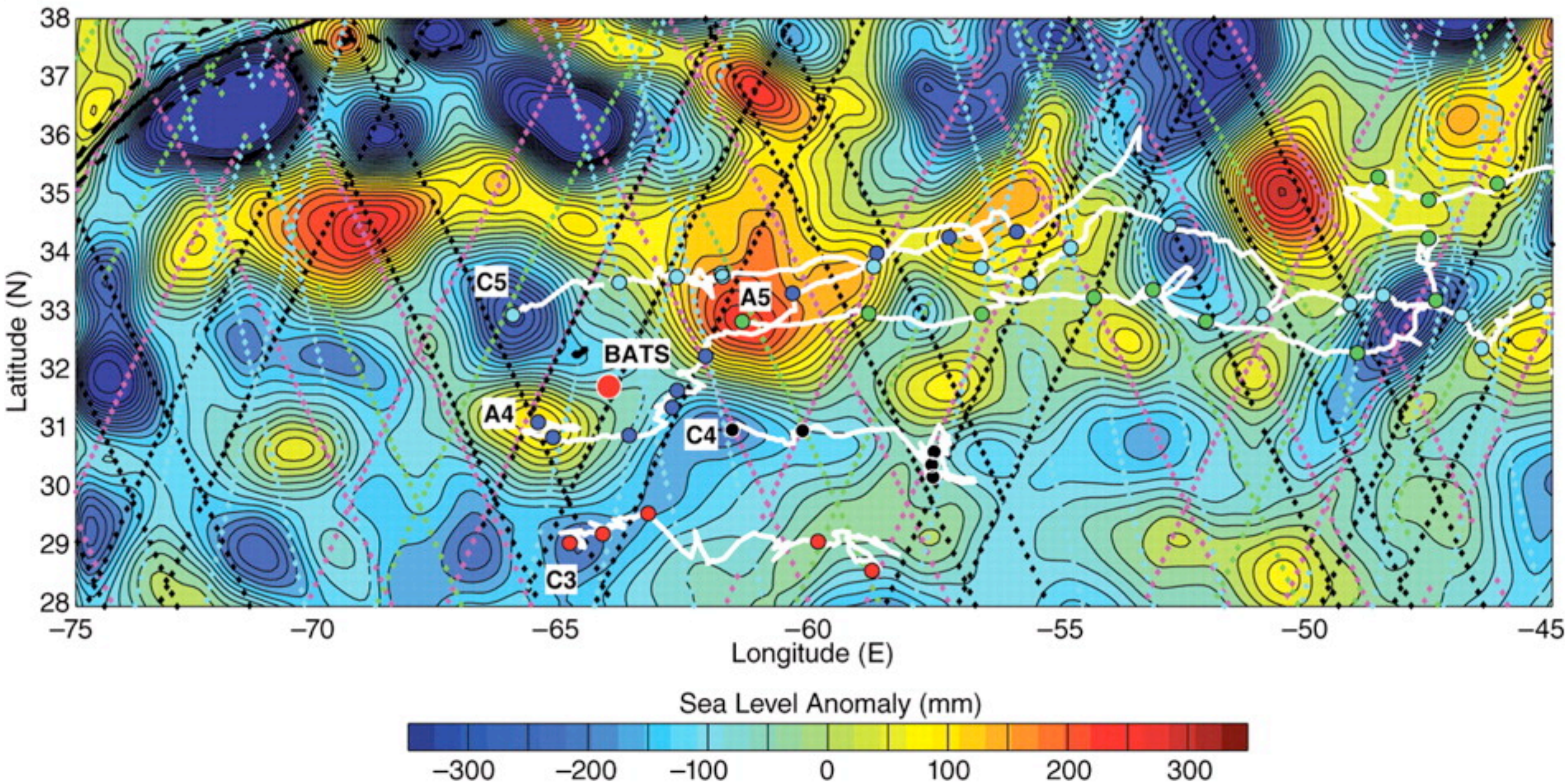


<u>Our Initial Hypothesis</u>:

- Cyclones & Mode-Water Eddies will have enhanced primary production as they form and intensify
- Anticyclones will not

After McGillicuddy et al. *Science* [1998]

Eddy Hunting Using Altimetry



EDDIES 2005 field year

McGillicuddy et al. *Science* [2008]

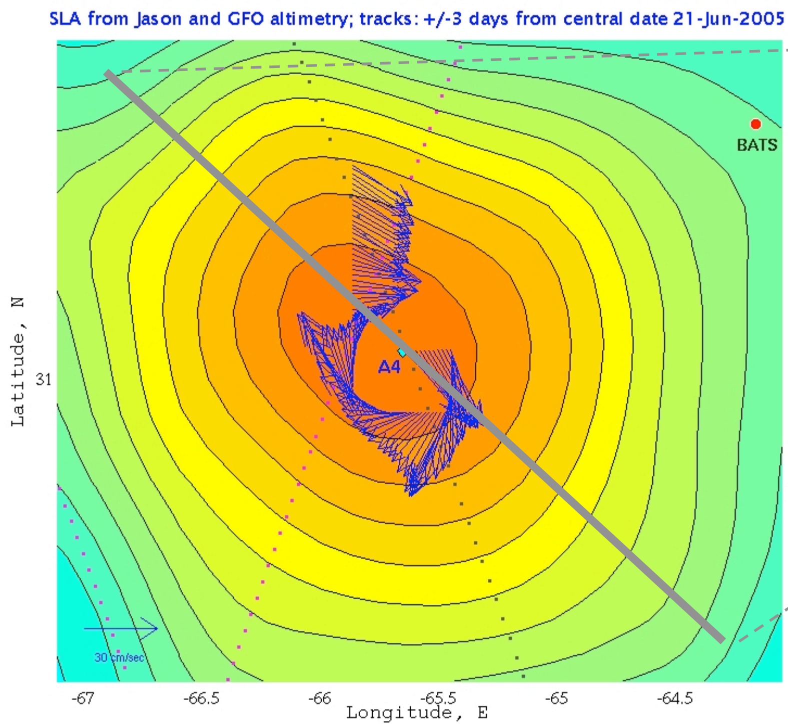
2004/2005 EDDIES Cruises

10 different eddies sampled, 5 more than once

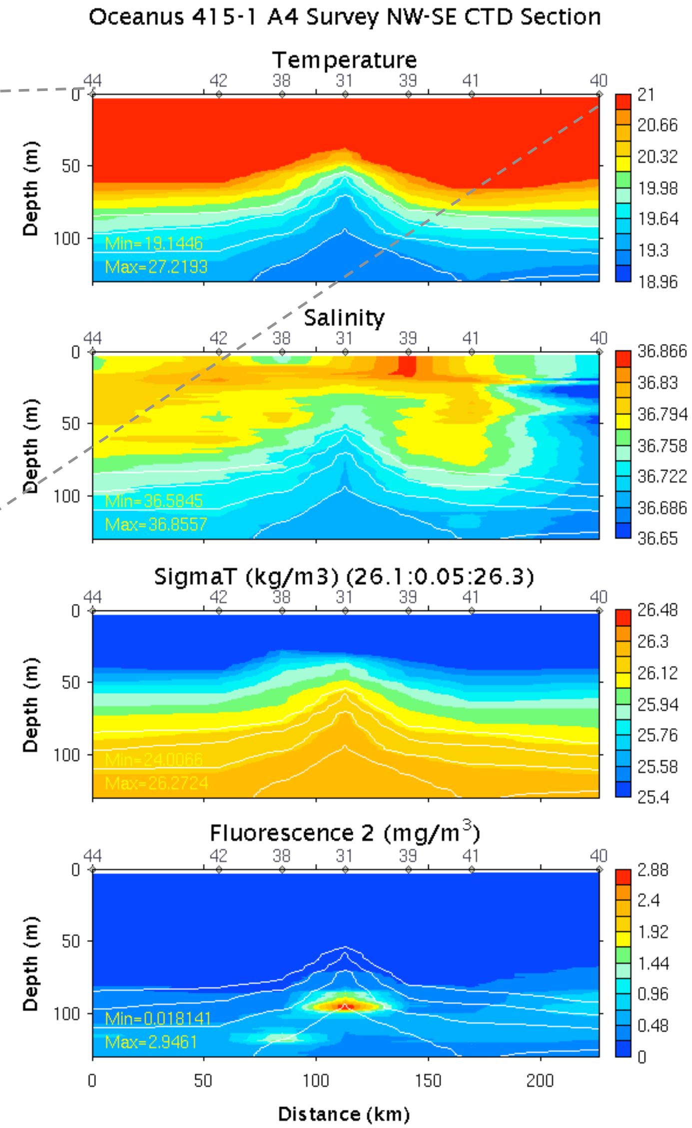
	occupations
Cyclones	
C1 – OC404-1 (3), OC404-4 (1)	4
C2 – OC404-1, OC404-4	2
Cold-core GS Ring	1
C3 – OC415-1	1
C5 – OC415-1 (2)	2
Anticyclones	
"Regular"	
A2 – OC404-1 (XBT/ADCP/VPR only)	1
A3 – OC404-1 (XBT/ADCP/VPR only)	1
18° Mode-water eddy	
A4 – OC415-1 (2), OC415-2, OC415-3 (2), OC415-4	6
16° Mode-water eddies	
A1 – OC404-1	1
A5 – OC415-1, OC415-3	2

Target Feature A4

Sea Level Anomaly



Cross Section

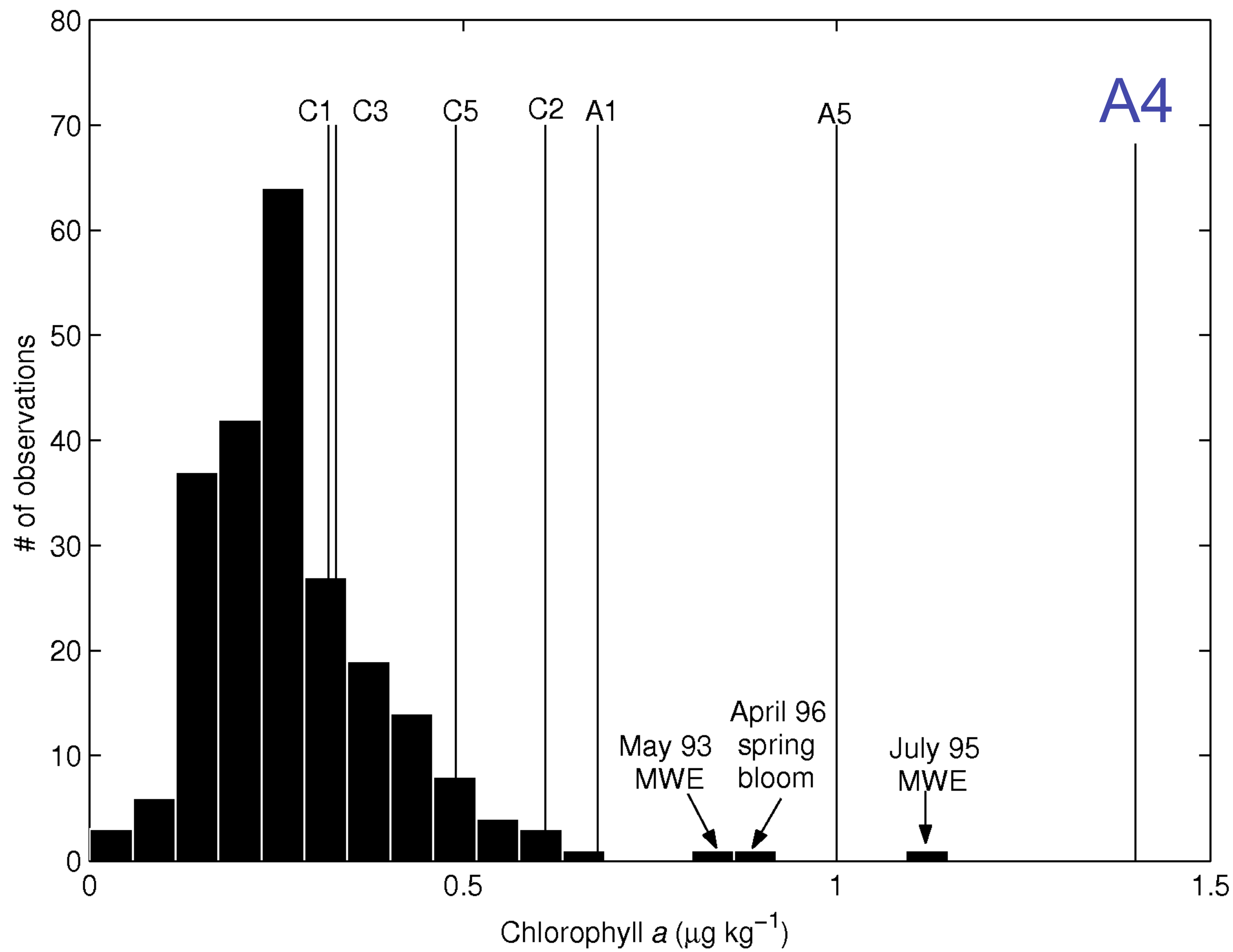


A4 is a Mode water eddy

Vertical displacement ~ 50 m

Chl increases in Chl max by 5X!!

BATS vs A4 Chlorophyll Maxima

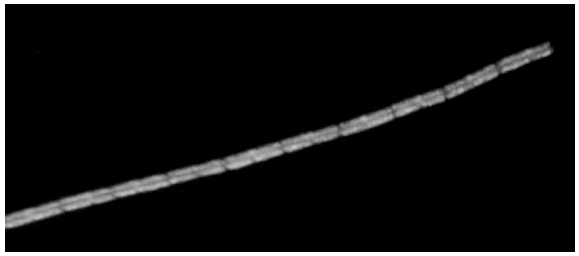


Chl in the A4 Chl max is higher than any found from BATS

Cyclones are lower than AC…

McGillicuddy & others *Science* [2008]

Diatoms in the A4 Chl Maximum



Chain forming diatom
Chaetoceros spp.

Diatom cell counts:

8000 colonies per liter X 15 cells per colony
= ~10^5 cells per liter

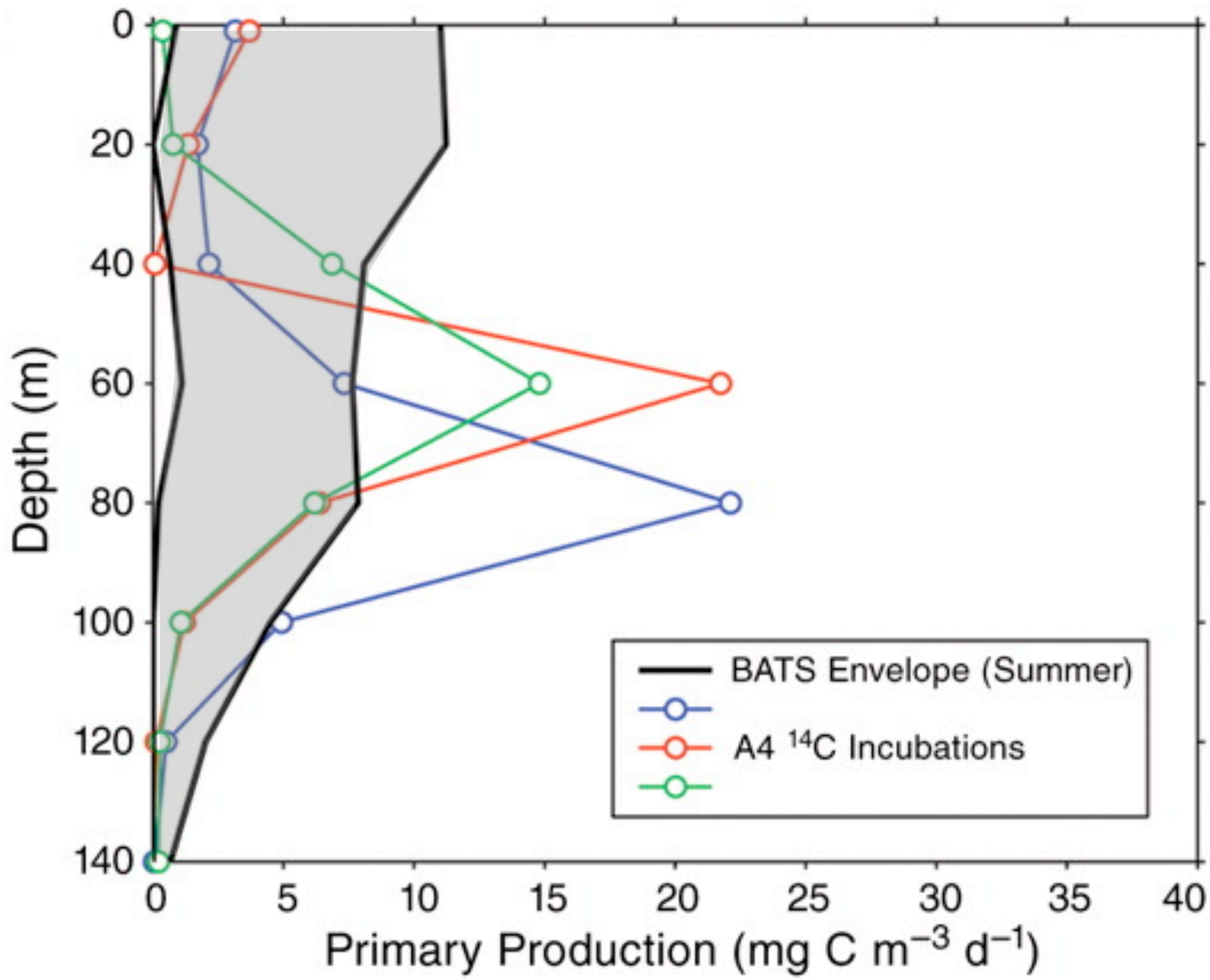
Typical abundances: 1-10 cells per liter

Eddy induced enhancement:

4-5 orders of magnitude above background

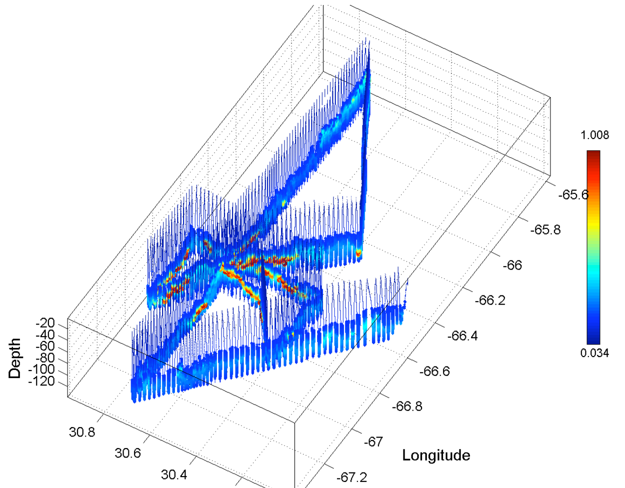
McGillicuddy et al. *Science* [2008]

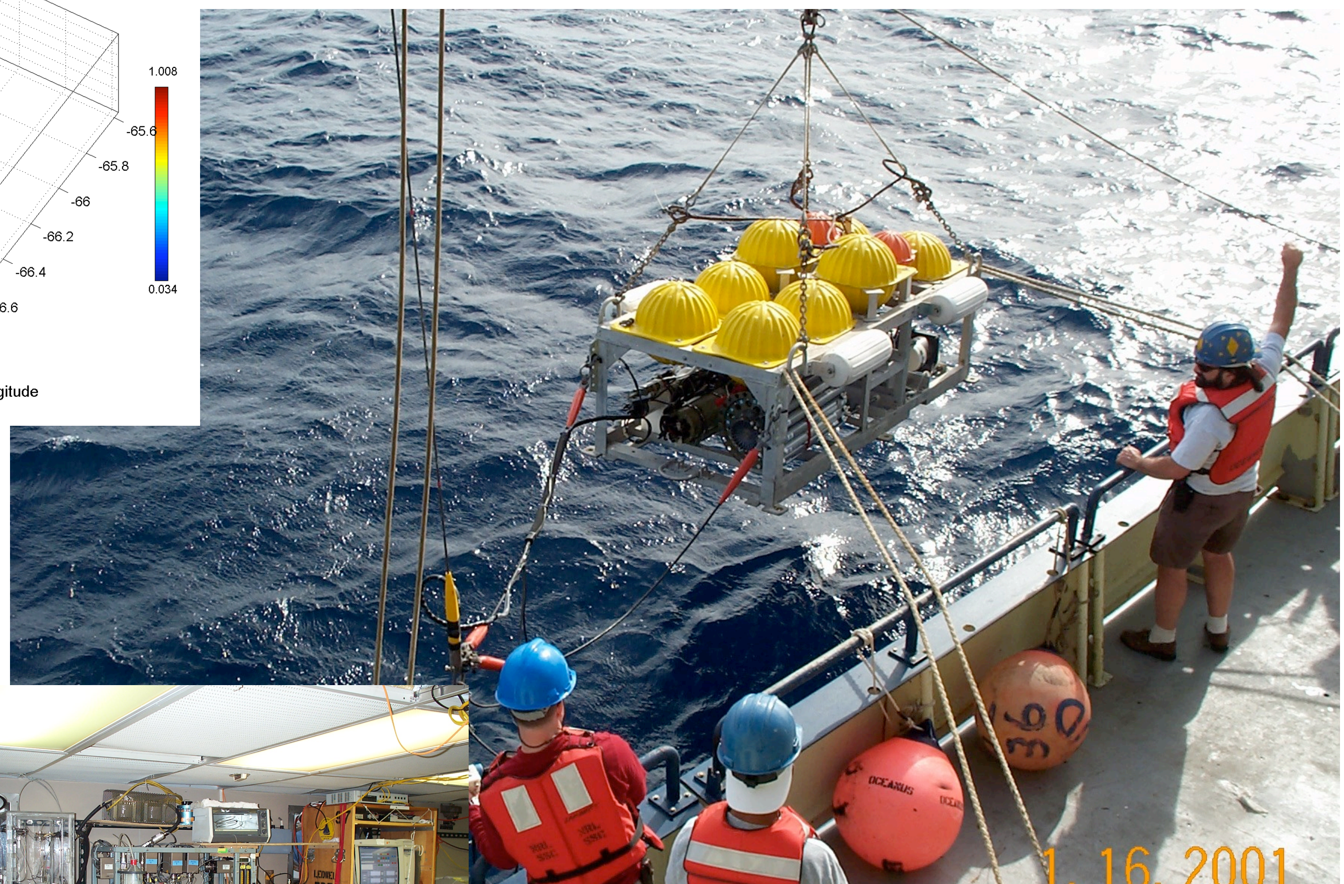
A4 Productivity vs. BATS



McGillicuddy et al. *Science* [2008]

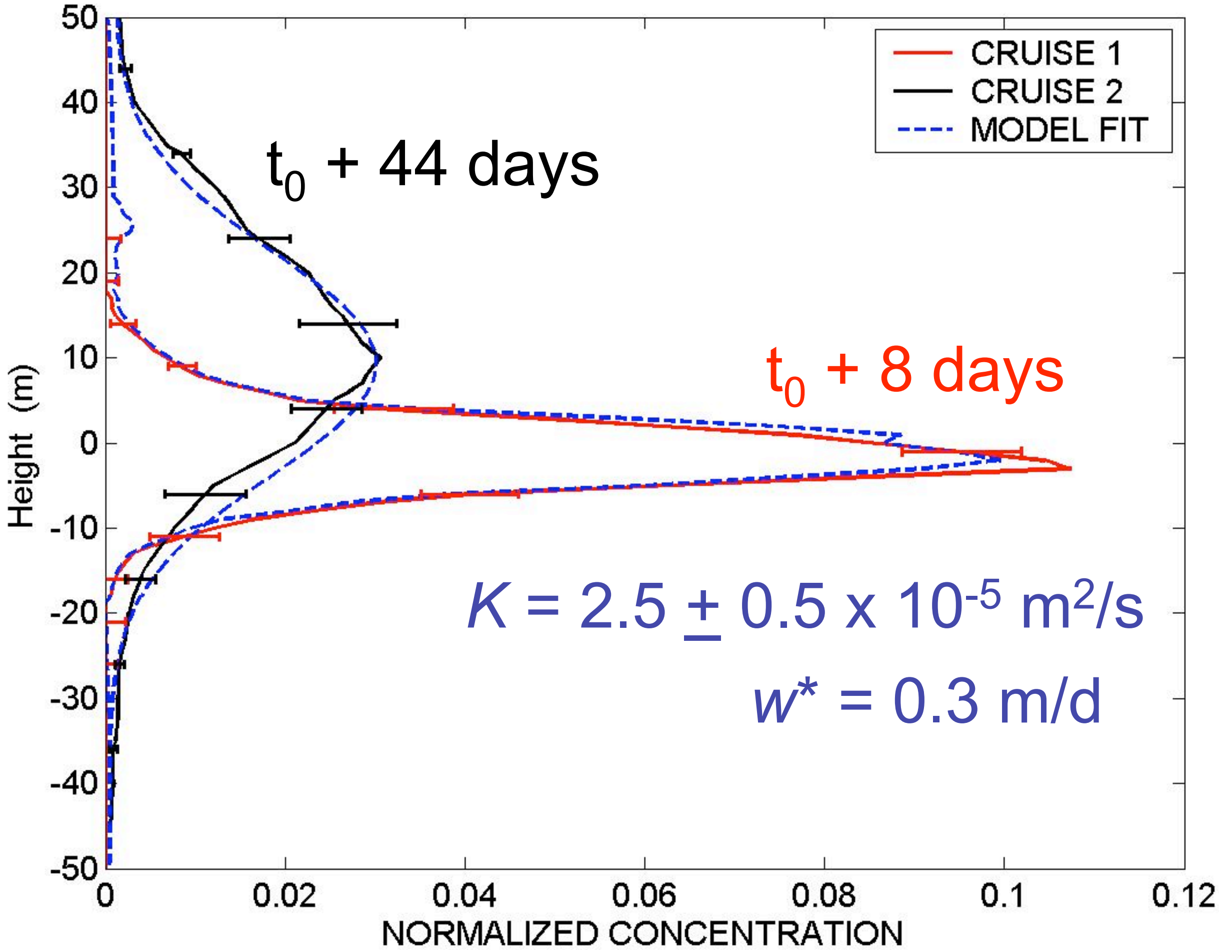
A tracer release provides a clue about the extraordinary productivity in A4





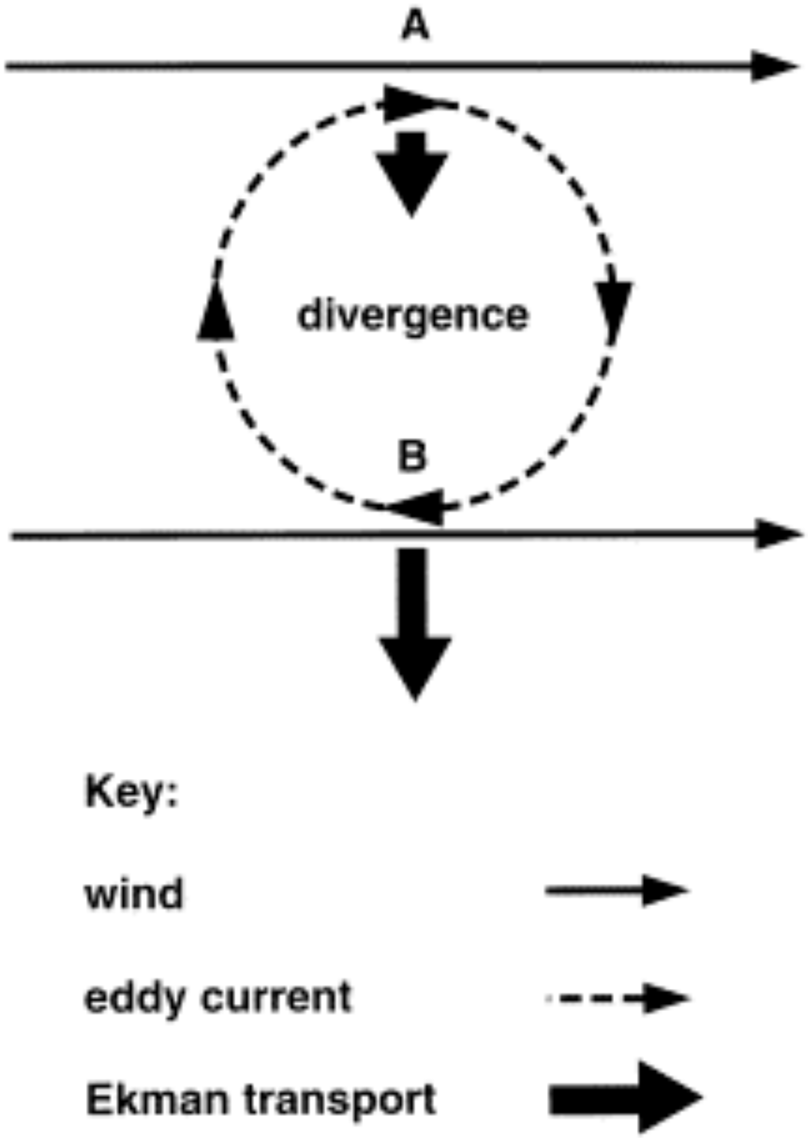
SF_6 Tracer Release (1.6 kg)
LOD: 1 part in 10^{18}

Tracers Reveal Upwelling & Enhanced Vertical Mixing



Ledwell et al., *DSR-2* [2008]

Upwelling by Eddy-Wind Interaction?



Ekman Pumping

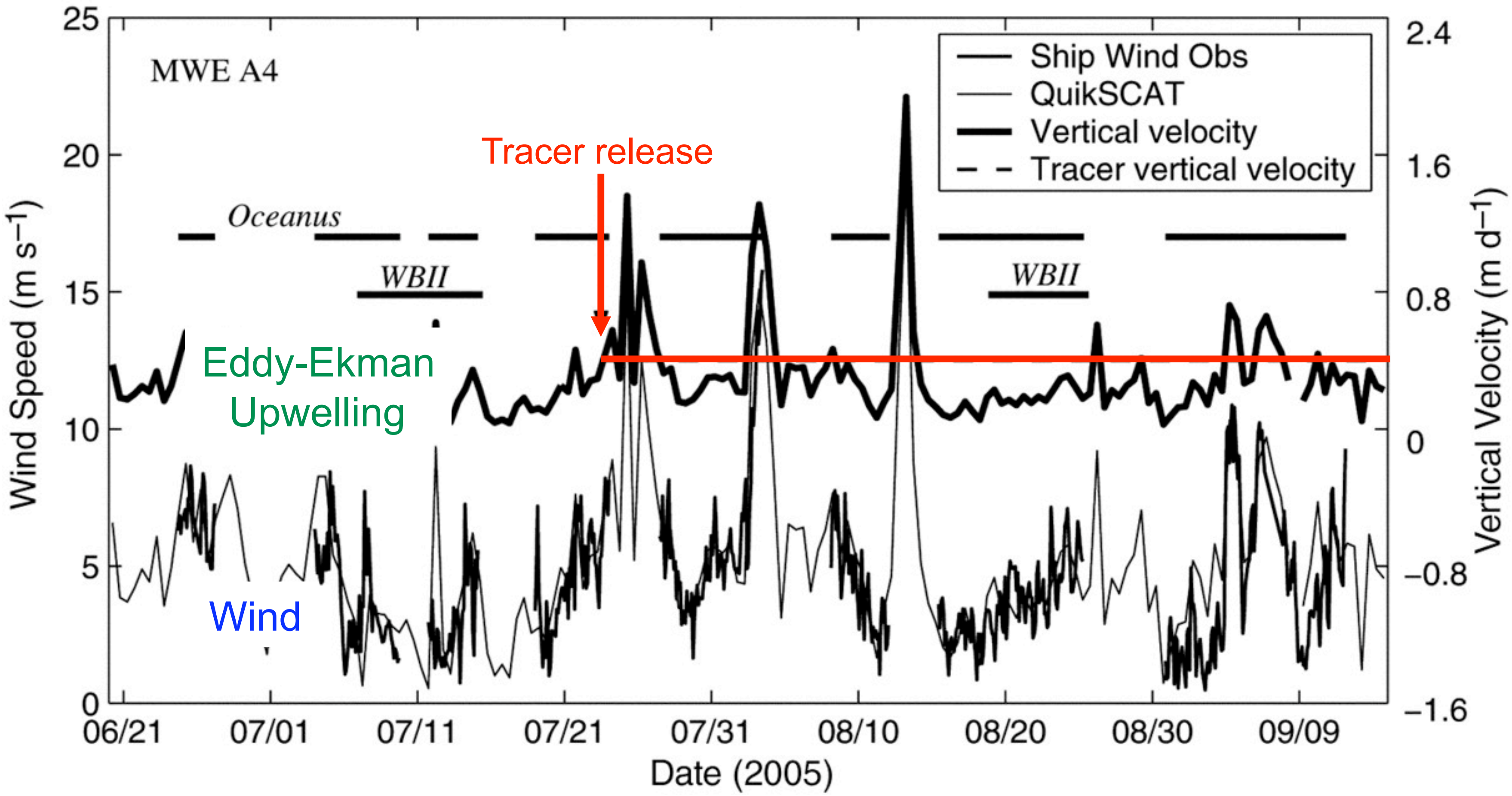
$$w_E = \frac{1}{\rho f}\left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}\right)$$

Stress is f(wind-current)

$$\tau = \frac{\rho_a K_a}{(1+\varepsilon)^2}\left|u_a - u_o\right|(u_a - u_o)$$

Dewar & Flierl, 1987
Martin & Richards, 2001

Upwelling by Eddy-Wind Interaction?

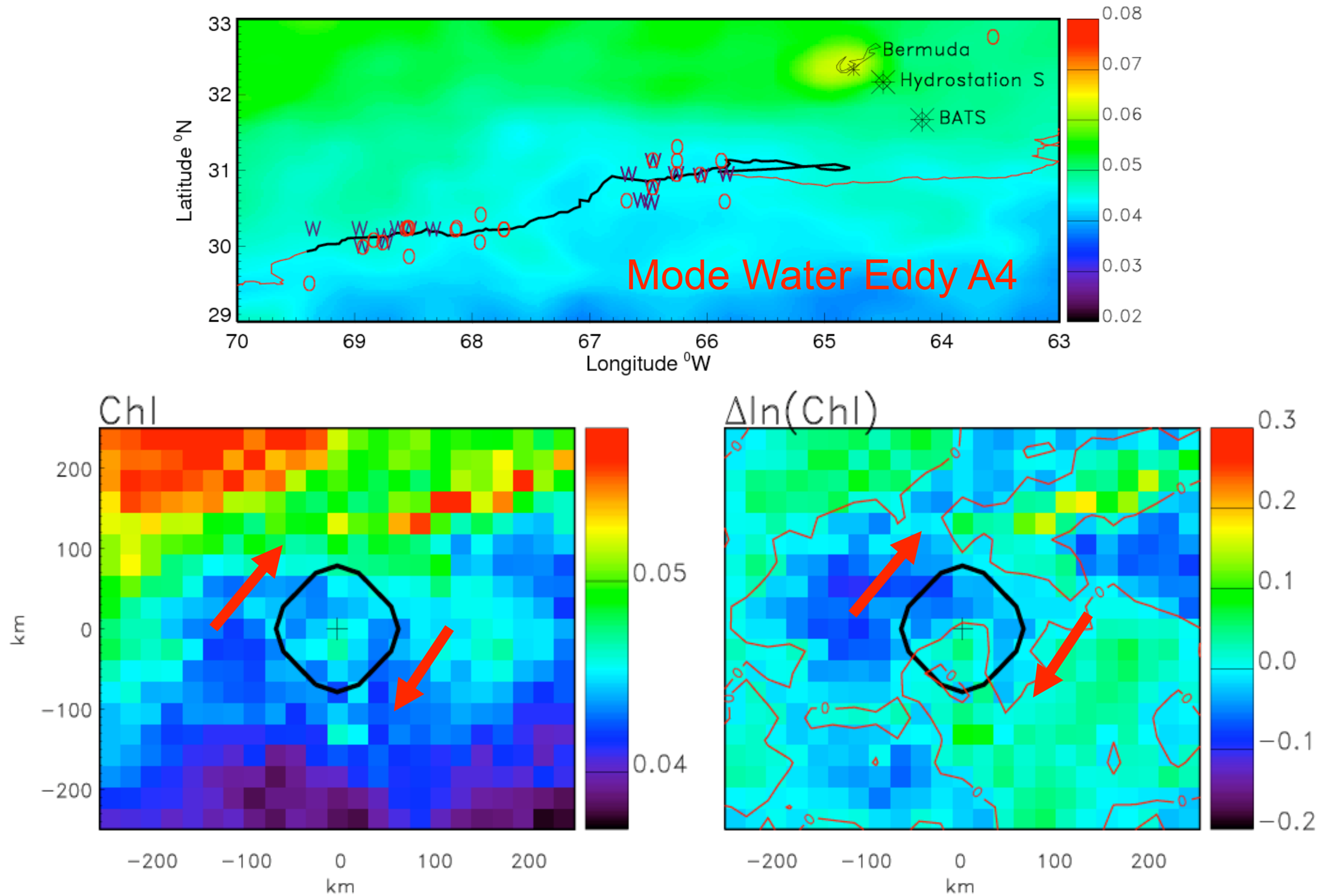


Simple theory is consistent with tracer upwelling estimates

Eddy-Ekman Pumping mechanism

McGillicuddy et al. *Science* [2008]

Eddy Centric Views of A4



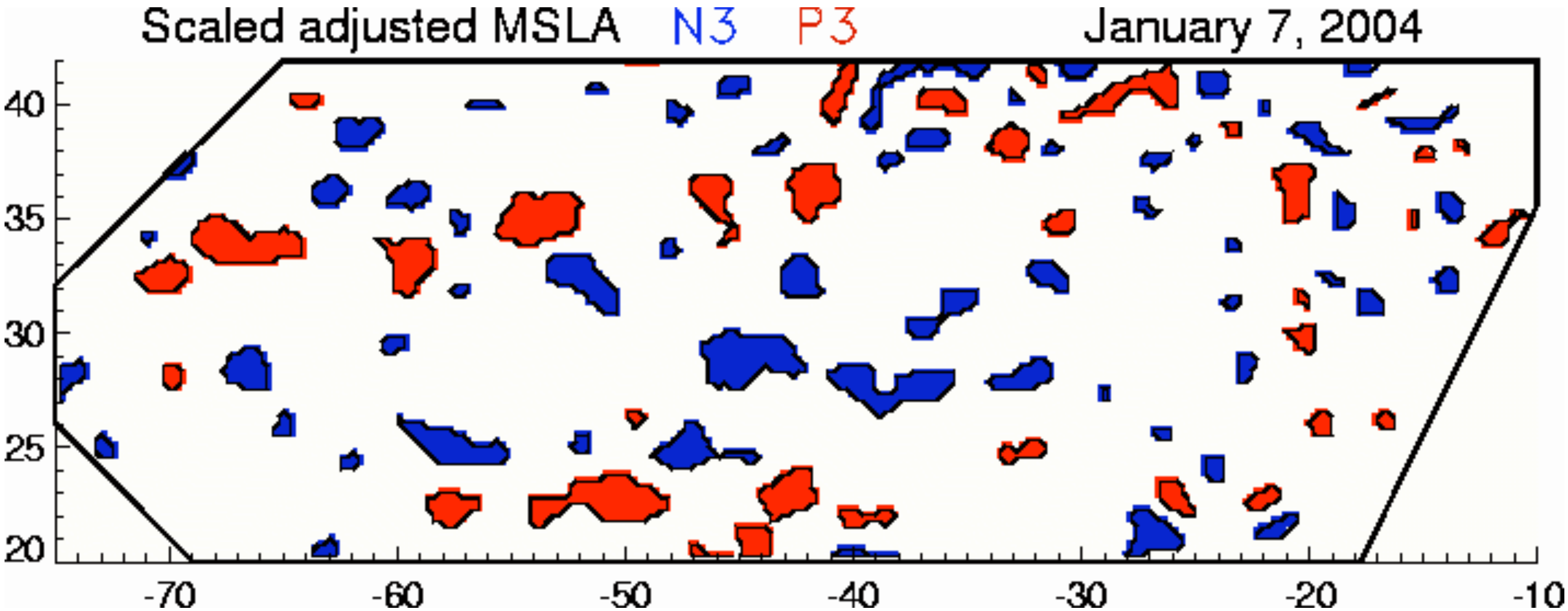
Satellite sensed Chl values following eddy A4 are small (& nearly unmeasurable…)

Provides sense of CW rotation of background Chl

Suggests an *Eddy Advection* Mechanism

Siegel et al. *DSR-II* [2008]

Views Over Many Eddies



Siegel et al. in prep.

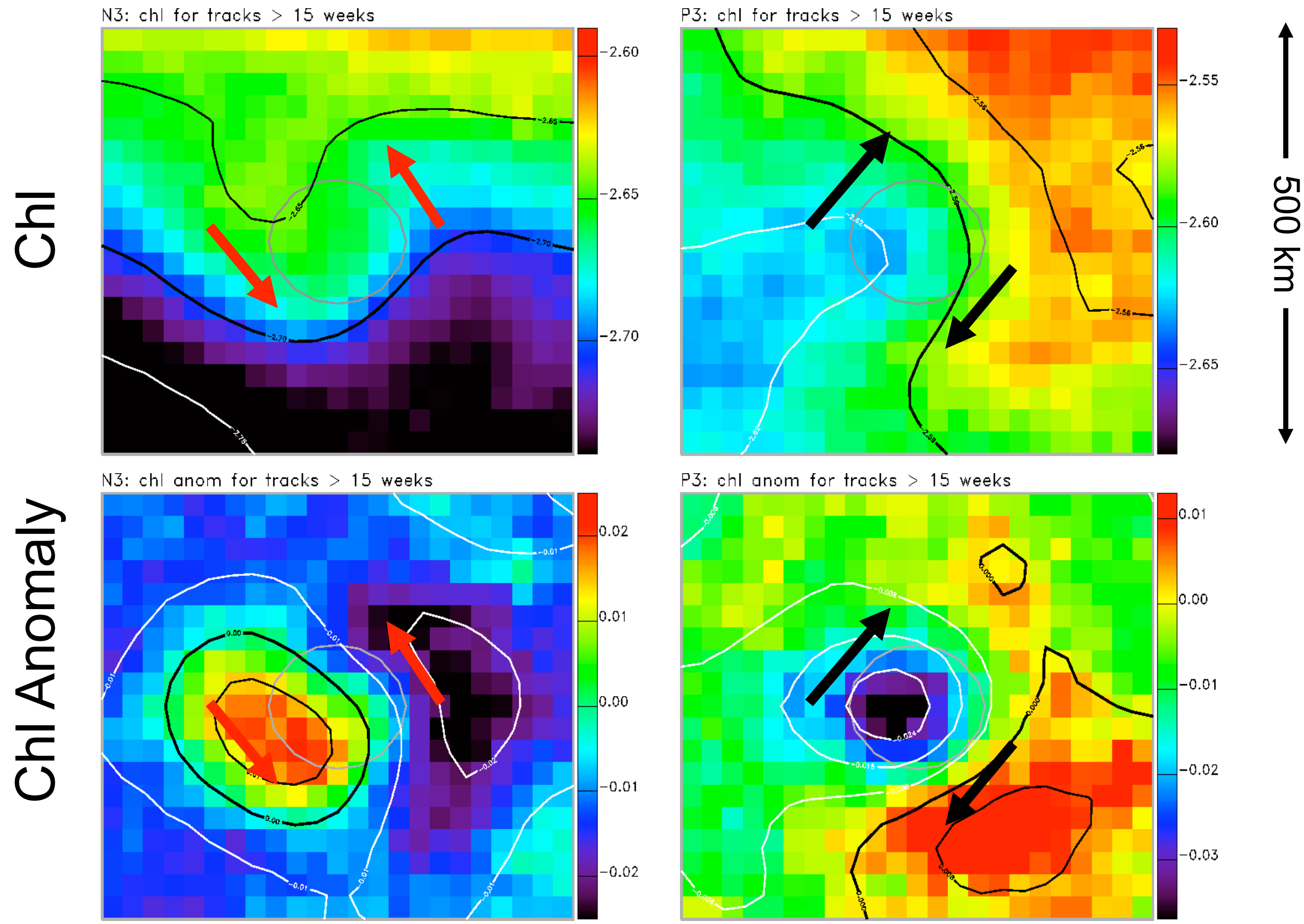
Merged sea level anomalies are filtered to asses eddy locations

Blue cyclones (CCW) & red are anticyclones (CW)

Tracked over time to assess eddy tracks

Provide an eddy-centric coordinate system to assess biological patterns

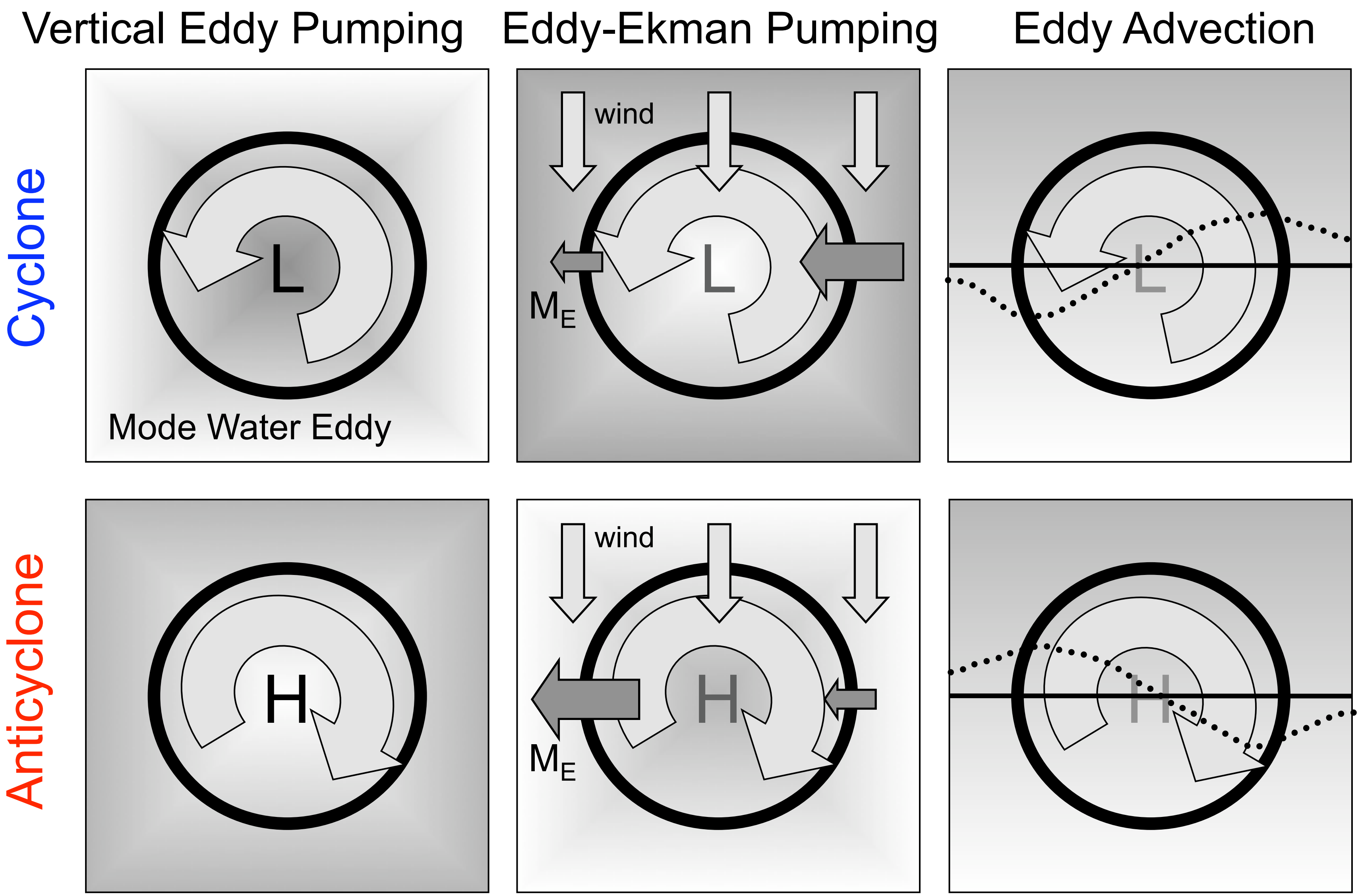
Cyclones (CCW) Anticyclones (CW)



Siegel et al. in prep.

Chl patterns following 5,161 cyclones & 3,804 anticyclones

Both *eddy pumping* & *eddy advection* signals are apparent



Not all mechanisms are biogeochemically relevant

BGC response is more often at depth

Siegel et al. *DSR-II* [2008]

EDDIES Summary

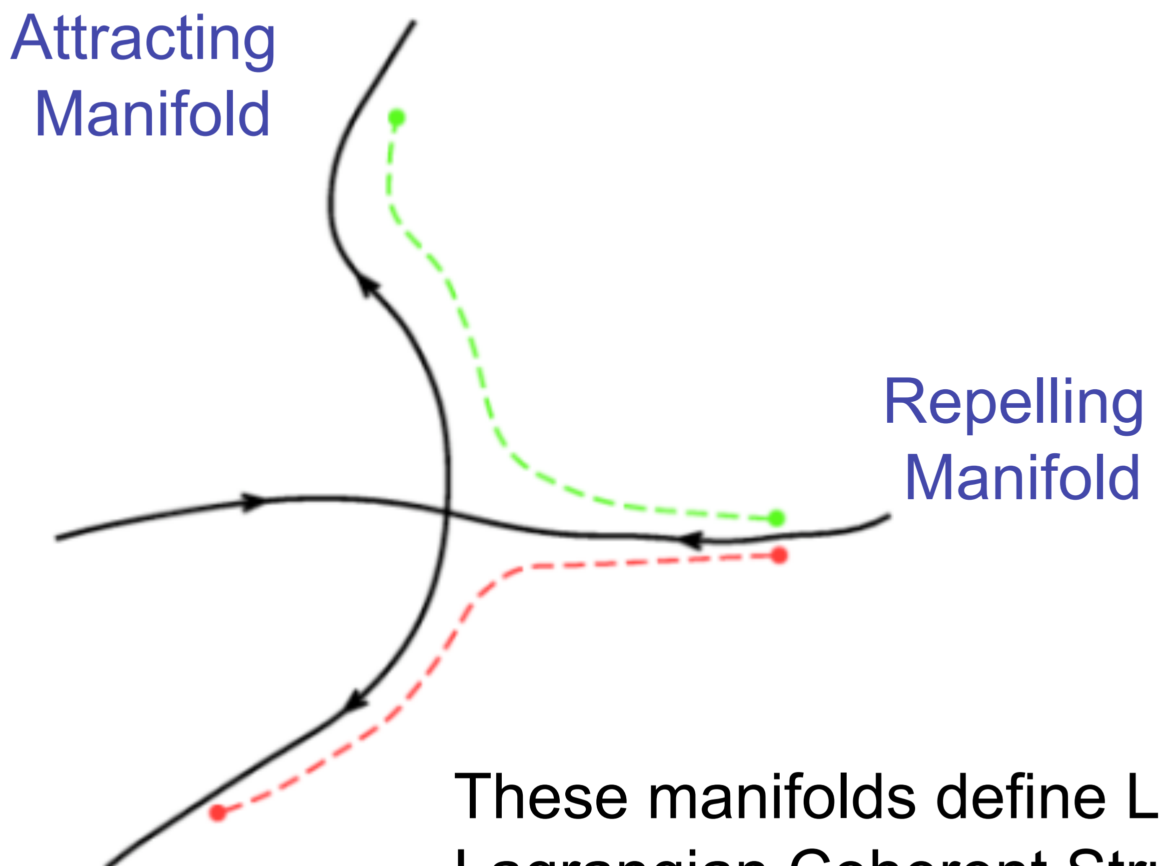
- Merged altimetry are great for hunting eddies
- Reponses are large in primary production, biomass & community structure - but subsurface
- Biological response of Anticyclones > Cyclones; contrary to original *Eddy Pumping* hypothesis
- Supports an *Eddy-Ekman Upwelling* mechanism
- Evidence for an *Eddy Advection* mechanism too

Uz et al. *Nature* [2001] & Killworth et al. *JGR* [2004]

Biological Role of Mesoscale Eddies

- Several mechanisms link eddies to ocean color signals, but not all are BGC relevant
  - Still many open questions…
- Hard part is assessing the subsurface & links from the euphotic zone into the ocean interior
  - Concentrated field efforts are needed
- New tools to assess physical-biological couplings…

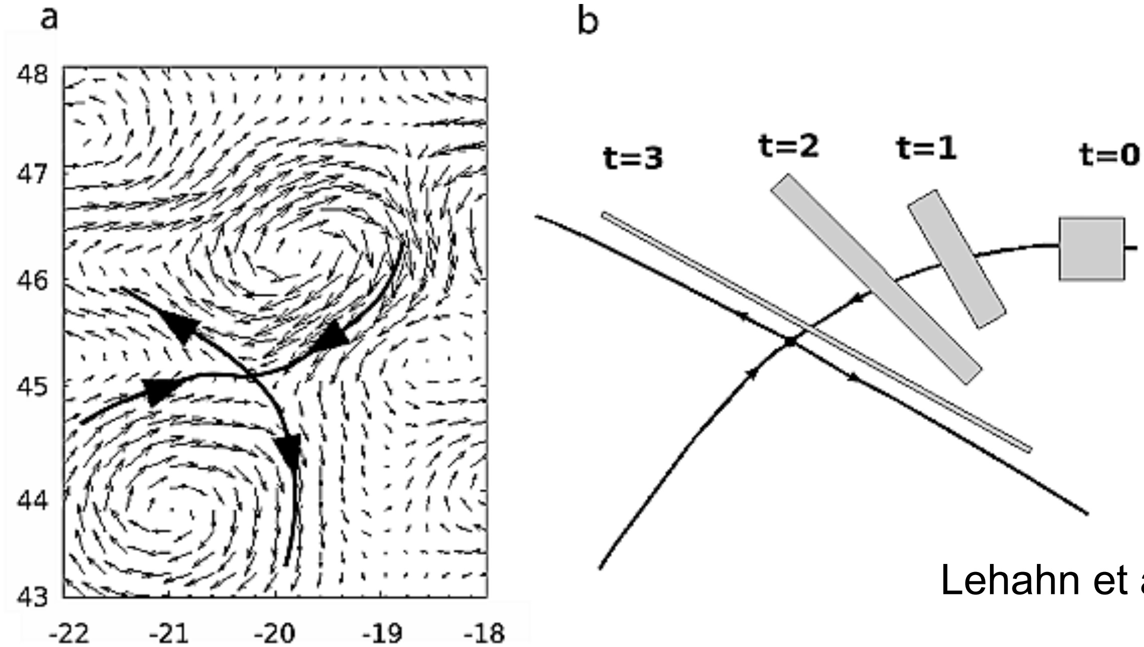
Lagrangian Coherent Structures



These manifolds define LCS's or Lagrangian Coherent Structures

Maybe they can provide some bio-eddy insights…

Attracting & Repelling LCS's



Lehahn et al. *JGR* [2007]

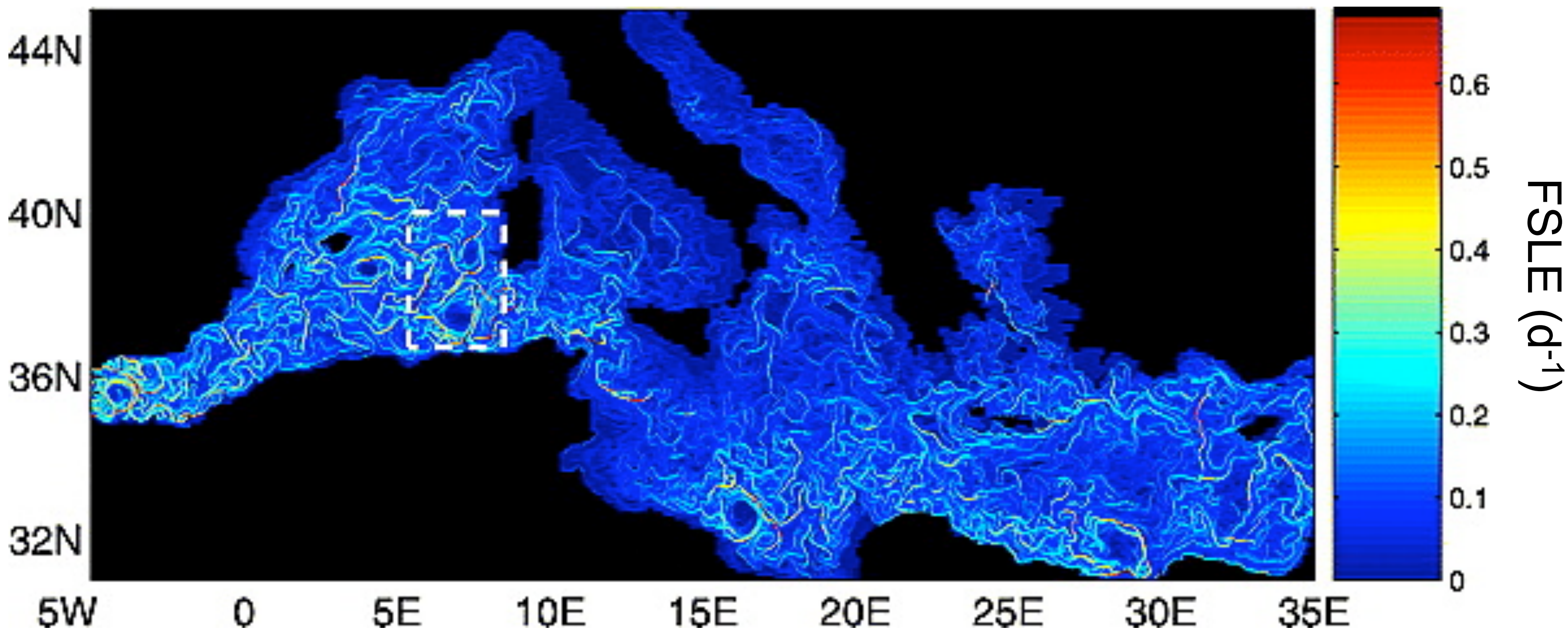
Measures the separation of particles as f(time)

Time scale of separation (Lyapunov exponent) characterizes repelling (forward in time) & attracting (backward) LCS's

Need a 2-D velocity field (model or obs; can be f(time))

Repelling & attracting LCS's have biological interpretation

LCS's in Mediterranean Sea



Repelling manifolds for one day in a 1/8^o circulation model

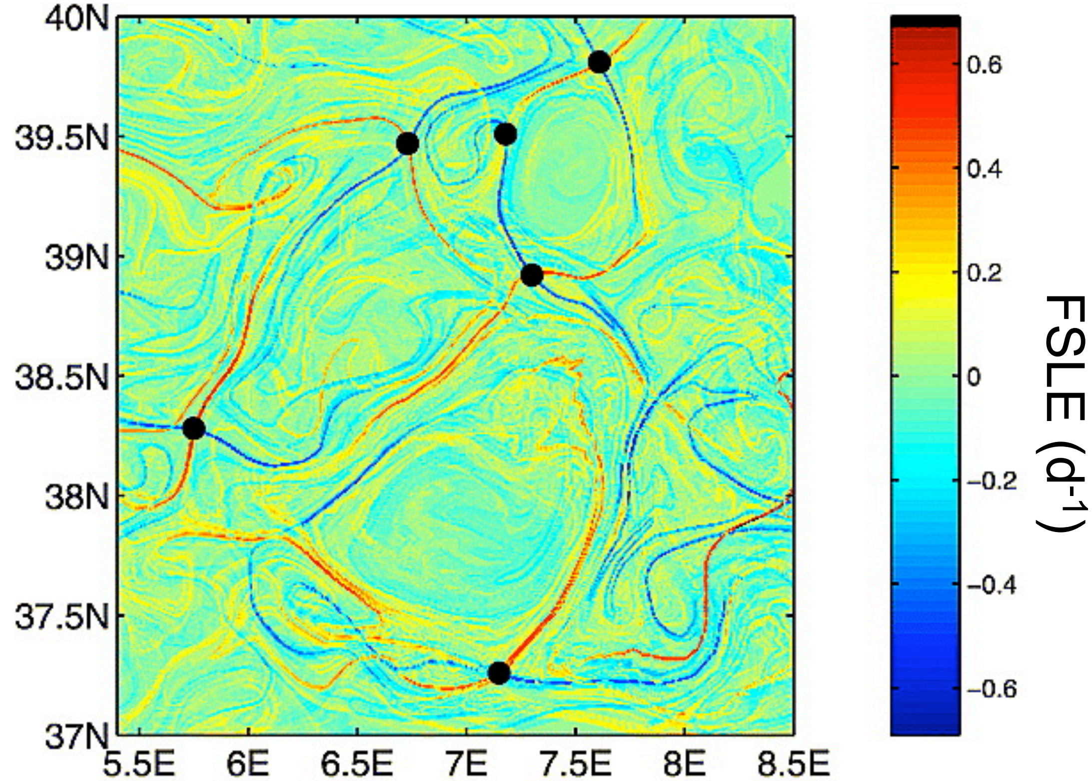
High values of FSLE "line up" creating "separatrixs" that differentiate the flow field into subregions (eddies, etc.)

Value of FSLE defines mixing time scale

D'Ovidio et al. *GRL* [2004]

LCS's in Mediterranean Sea

- Red repelling & blue attracting LCS's
- Coherent structures for both repelling & attracting FSLE's
- Structure widths are narrow (a few km's)
- Biologically relevant interpretations - repelling LCS's are divergent & attracting LCS's are convergent



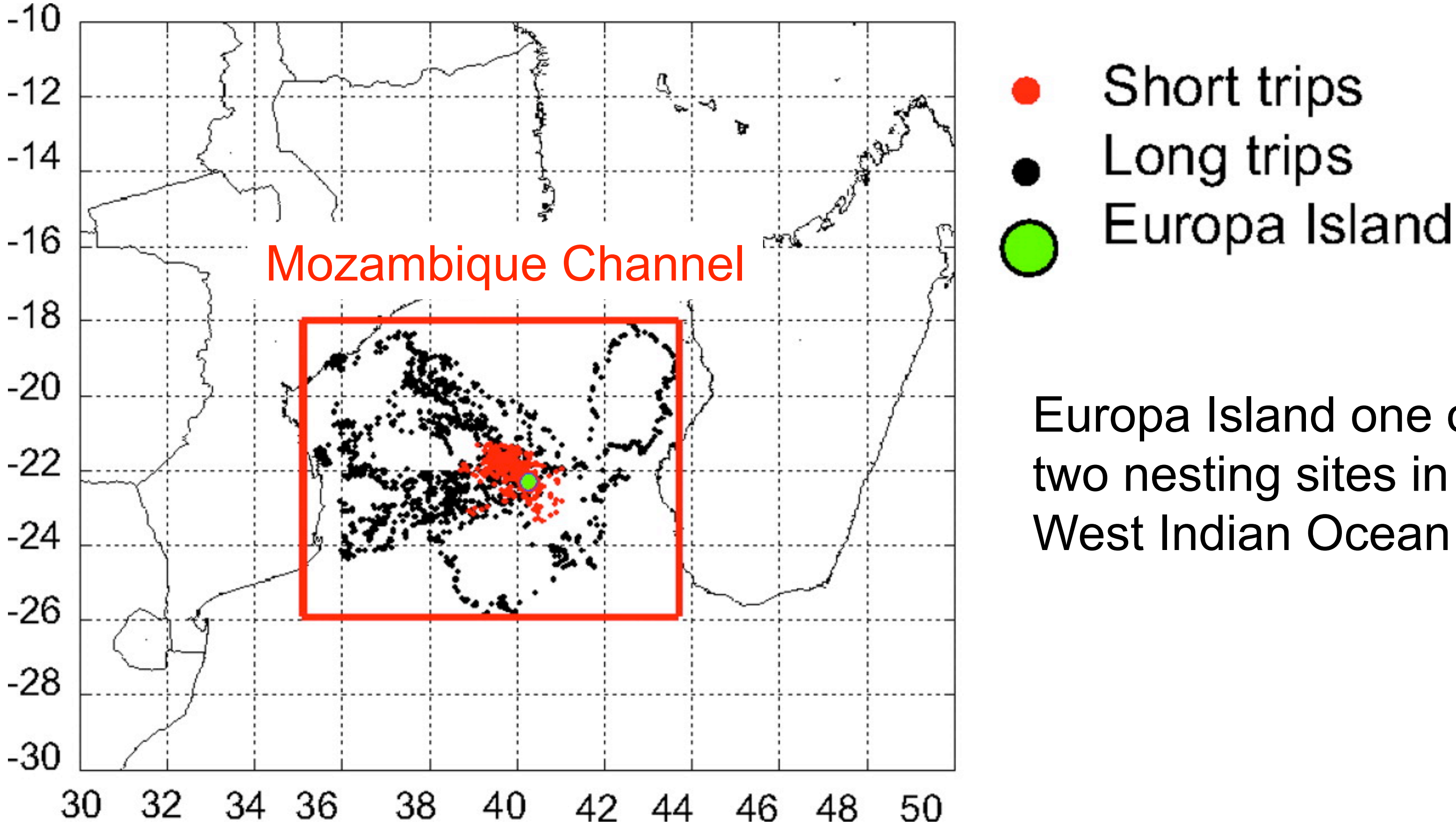
D'Ovidio et al. *GRL* [2004]

Great Frigatebirds

- Can fly great distances to forage
- Diet made up of flying fish & Ommastrephid squid
- Frigatebirds cannot get wet
- Sometimes a klepto-parasite
- Often found foraging in association with tuna & dolphin schools
- Great frigatebirds are a top predator found throughout the tropical oceans

Tew Kai et al. *PNAS* [2009]

Great Frigatebird Foraging



Europa Island one of two nesting sites in the West Indian Ocean

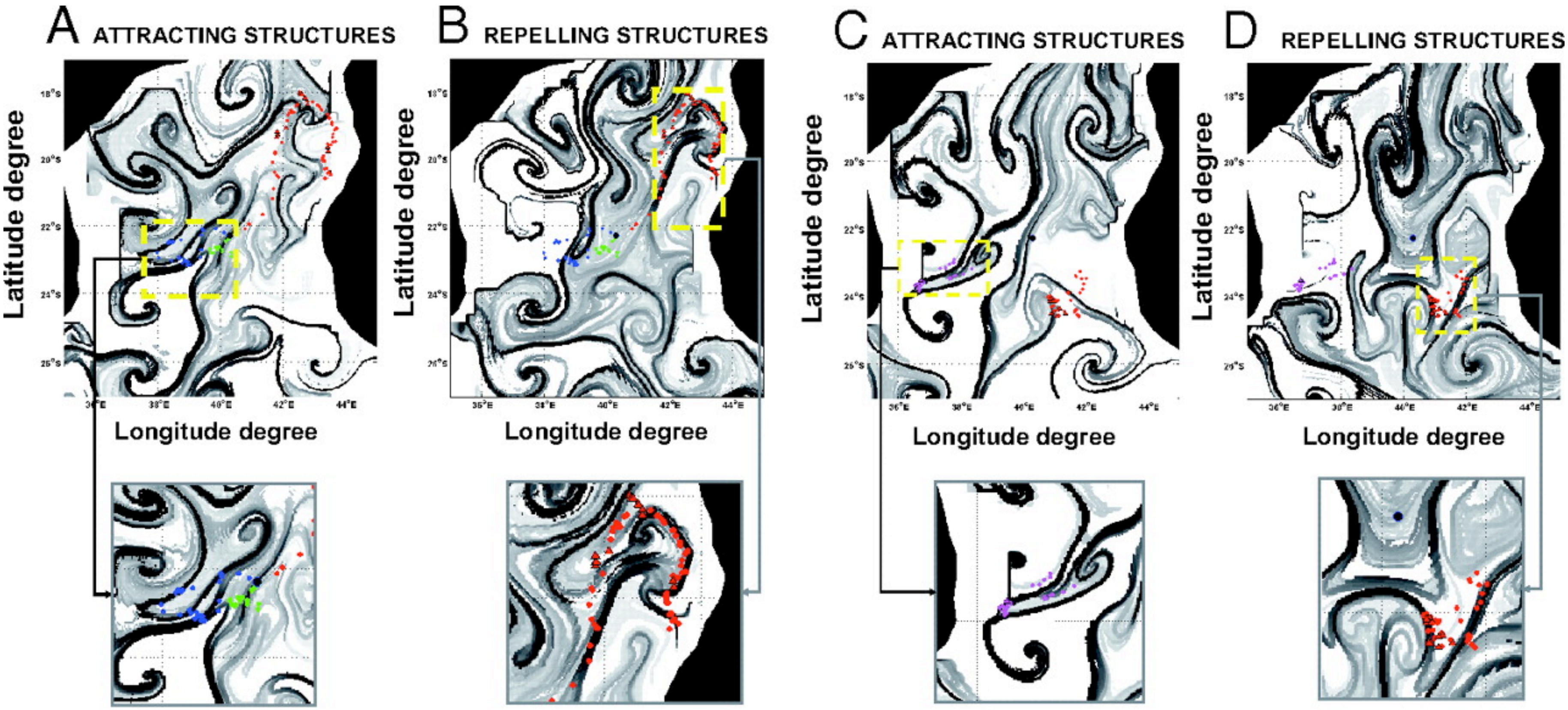
Argos locations of Great Frigatebirds during long trips (black) & short trips (red) between August 18 & September 30, 2003

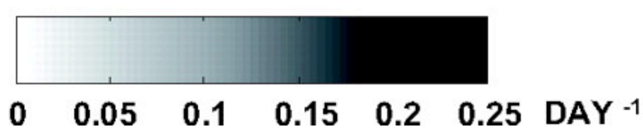
Tew Kai et al. *PNAS* [2009]

Great Frigatebird Foraging & LCS's

Week Sept 24, 2003

Week Oct 6, 2003

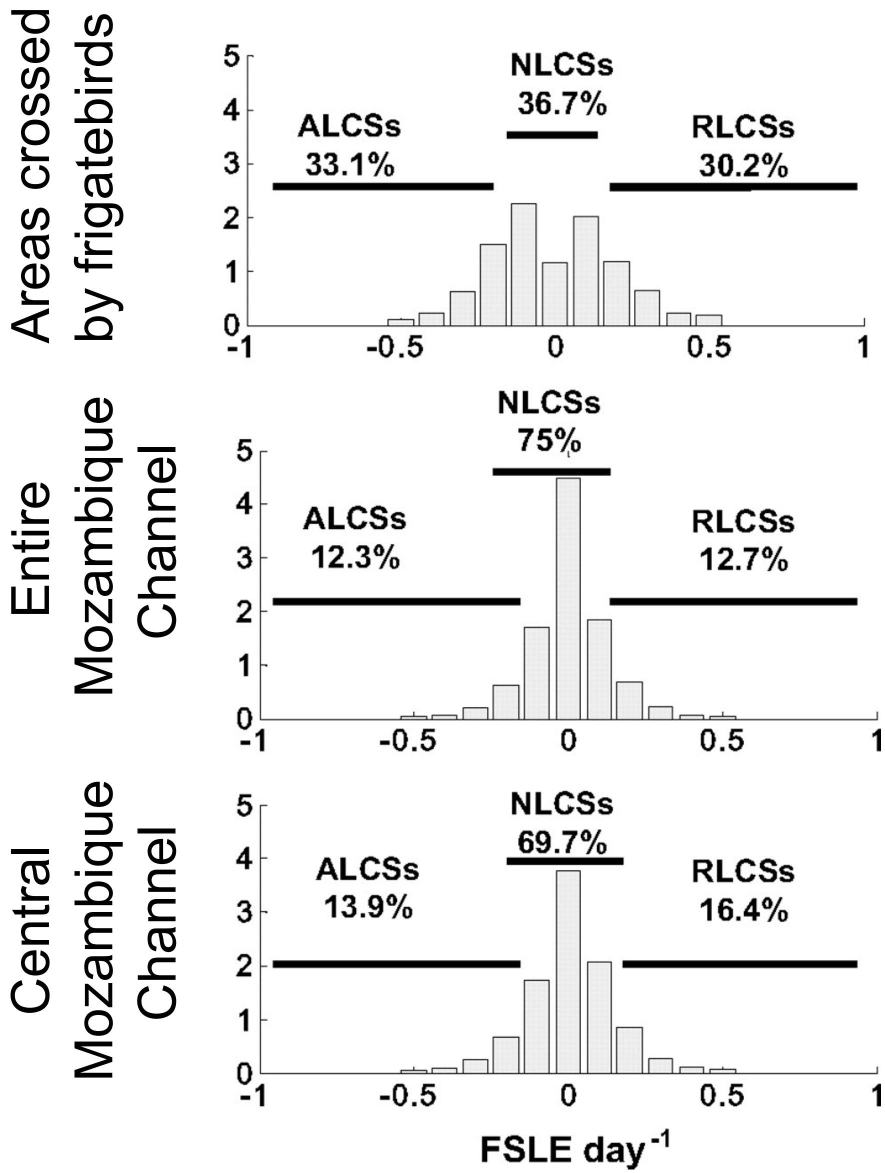




Used altimetry & winds
to calculate FSLE's

Tew Kai et al. *PNAS* [2009]

Great Frigatebird Foraging & LCS's



Frigatebirds are found over LCS's >63% time

Overall, LCS's are "neutral" 70-75% time

Near-equal propensity for attracting & repelling LCS's

Attracting LCS's likely will help in active foraging

Repelling LCS's may help in navigation by smell (via DMS??)

Tew Kai et al. *PNAS* [2009]

Ocean Biology & LCS's

- LCS's characterize straining of the surface flow
  - Local regions of upwelling & downwelling
  - Convergence & divergence of water masses
- Applications in a wide host of problems
  - Fishery oceanography, Purposeful Fe addition, Linking euphotic & twilight zone processes via aggregate production, Pollution monitoring & mitigation, Search & rescue, etc.
- Easy to calculate given quality velocity fields

Future for Pelagic Bio-Eddy Science

- Continued quality observations are key

  Both altimetry (future=good) & ocean color (not so good)

- NASA's Decadal Survey Missions

  SWOT - 1 km sea level fields

  ACE, Geo-CAPE & HyspIRI - ocean color on many time / space scales & by different ways

- Robust links to field observations

  Process studies are needed to link to ocean interior

  Gliders, ARGO floats, etc.

  Operational 4-D circulation models

Thank you!

Dennis McGillcuddy, Dudley Chelton, Mete Uz for help preparing the talk

NASA GSFC Ocean Color Data Processing Group for creating the SeaWiFS & MODIS Aqua data sets shown

CNES AVISO for merged altimetry data

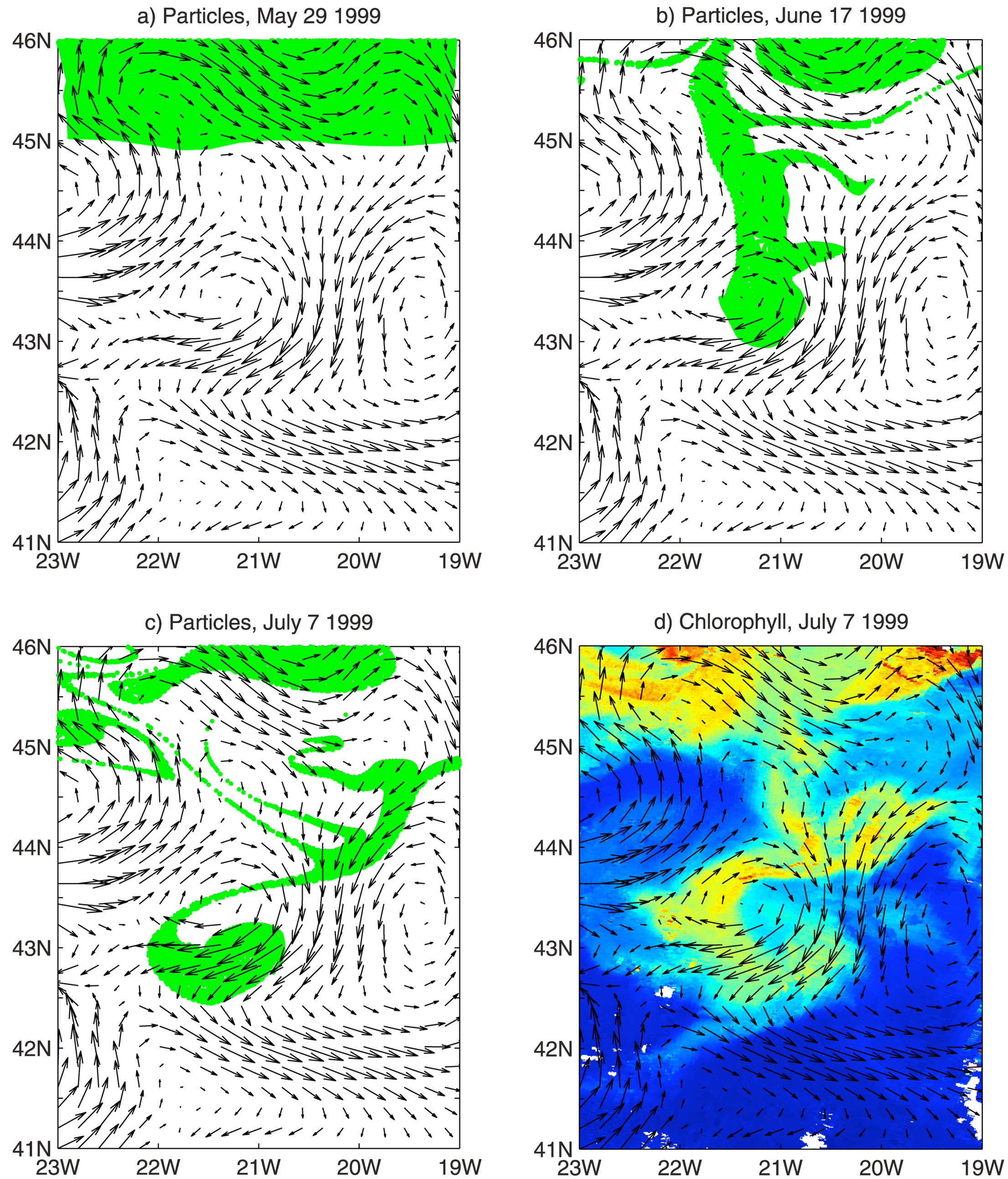
Role of Advection

Decay of the North Atlantic spring bloom

Flow fields from MERCATOR operational model

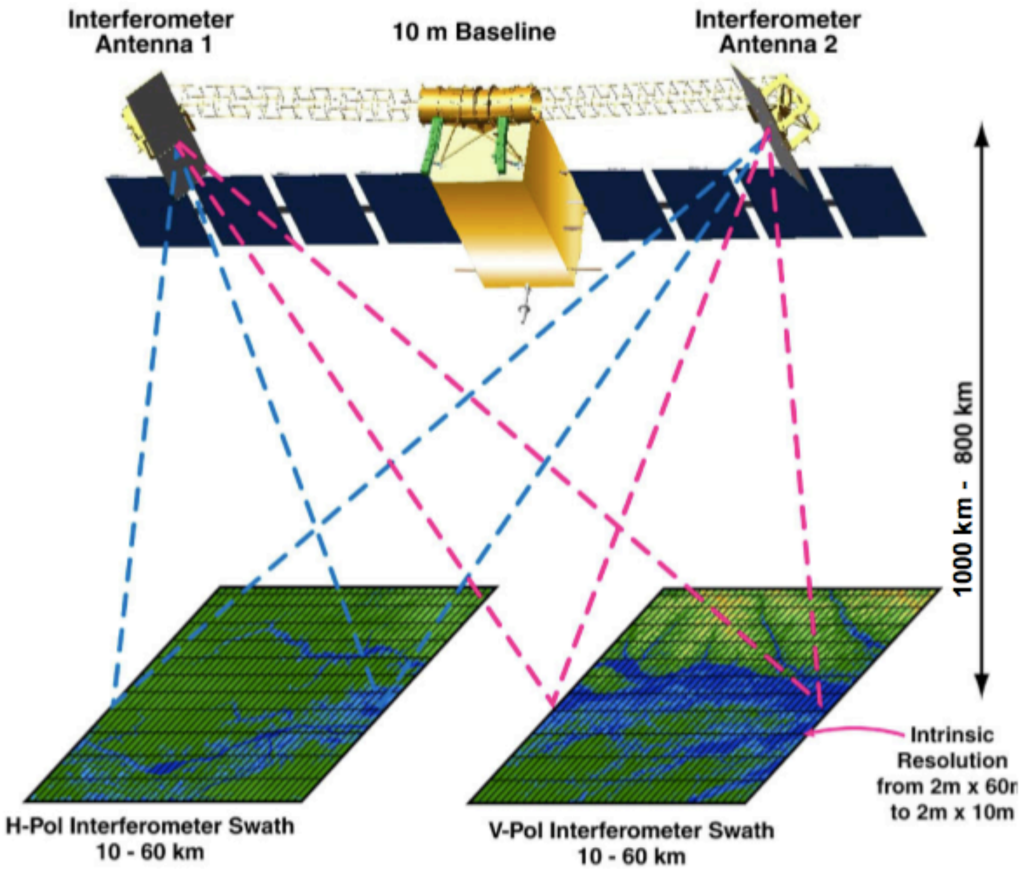
Passive particles placed north of 45^{o}N

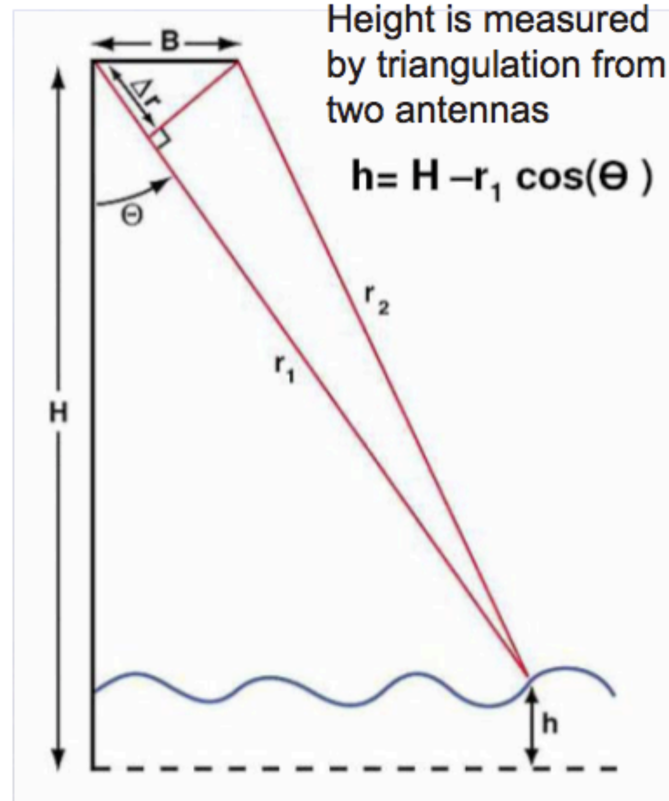
Particle distribution & Chl image are eerily similar on July 7



Lehahn et al. *JGR* [2007]

SWOT Synthetic Aperture Radar (SAR) Interferometer





SWOT is a Ka-band (~35 GHz) SAR interferometric system with two 60-km swaths separated by a 10-km nadir gap.

The spatial resolution of the SAR is ~50 m for measurements of land surface water (lakes, wetlands and rivers) for hydrology studies.

For oceanographic applications, the raw measurements will be averaged over 1 km by 1 km cells to achieve a measurement accuracy of ~1 cm.